UNIVERSITY OF CANTERBURY

DOCTORAL THESIS

Emotion Sharing in Virtual Reality

Author:
Hao CHEN

Supervisor:
Prof. Robert W. LINDEMAN
Prof. Mark BILLINGHURST
Dr. Gun LEE

A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

in the

The Human Interface Technology Laboratory New Zealand

December 10, 2019

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- Where I have consulted the published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of help.
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Date: December 10, 2019

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Abstract

The Human Interface Technology Laboratory New Zealand

Doctor of Philosophy

Emotion Sharing in Virtual Reality

by Hao CHEN

The primary goal of this thesis is to explore the effects that sharing emotional cues through physiological feedback has on overall emotional states of the users in both single-user and collaborative applications.

The motivation of this research has been derived, in part, from the work being undertaken by my co-supervisor Prof. Mark Billinghurst in the emerging field of *Empathic Computing*. He illustrated "Empathic Computing requires a combination of rich natural collaboration, capturing the user experience and surroundings, and being able to implicitly understand user emotion and context". This thesis explores the aspects of capturing, interpreting and sharing the user experience in virtual environments by way of physiological data.

In this thesis, five user studies were conducted in order to study how physiological data could be recorded, classified and shared amongst individuals in a multi-user VE with the aim of evoking empathy. Validation of a multi-sensory physiological feedback system is detailed in Chapter 3. This demonstrates that individuals prefer an audio-haptic feedback system when being provided with heart rate data. Results from a follow-up study (Chapter 4) demonstrate that artificially manipulating physiological data parameters shared with an individual has a significant effect on the observer's physiological signals. The rest of the studies detailed in this thesis take an application-based approach to the research question and implement the findings in multi-user VEs to study the effects of sharing physiological data in a VE during a shared experience.

The results of these studies demonstrate that sharing physiological cues between users of a VE helps generate positive affect i.e. the individuals feel a greater sense of connectivity amongst each other, and report higher levels of presence. Sharing of the physiological cues also appears to help users get a sense of each other's emotional states in the VEs. These findings demonstrate that sharing physiological data, representative of emotions, amongst users in a VE has the ability to improve interactions by way of eliciting empathy. Also, by manipulating physiological feedback, emotions of users could be affected to some extent.

Acknowledgements

During my PhD, I got lots of help from the people around me. At this stage, I would like to show my deepest gratitude to them.

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It is hard for me to express my gratitude to my mother. Thank you for always believing and supporting me when others are doubting me. Thanks to my older brother and his family for taking care of my mother when I am away. Also, I would like to thank my father for teaching me so much to be a good and brave man. Even now he is not with me anymore but I believe he would surely support me to finish my PhD. Also huge thanks to my partner Jing Li. Thank you for accompanying me for so many years when I am in trouble and thank you for the great memories in the past eight years.

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Chen, Hao, Arindam Dey, Mark Billinghurst, and Robert W. Lindeman. "Exploring the design space for multi-sensory heart rate feedback in immersive virtual reality." In *Proceedings of the 29th Australian Conference on Computer-Human Interaction*, pp. 108-116. ACM, 2017.

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The study was consulted with Mark Billinghurst and Arindam Dey. I designed almost all the user study system including most of the software and all the hardware integration and collected all the study data. Mark Billinghurst and Arindam Dey gave good feedback on the user study design. Mark Billinghurst and Rob Lindeman helped review and edit the paper and gave good feedback after the paper draft was finished. Arindam Dey also helped analyze the study data. Arindam Dey edited most of results and discussion sessions. My contribution is more than 65%.

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The study was consulted with Mark Billinghurst and Arindam Dey. I designed almost all the user study system including most of the software and all the hardware integration and collected all the study data. Mark Billinghurst and Rob Lindeman helped review and edit the paper and gave good feedback after the paper draft was finished. Chang Zhuang helped design one VR scene in the user study. Arindam Dey finished all the data analysis and finished most of the editing in the sessions of results and discussion. My contribution is more than 70%.

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Chen, Hao, Arindam Dey, Mark Billinghurst, and Robert W. Lindeman. "Exploring pupil dilation in emotional virtual reality environments." (2017).

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Name: *Mark Billinghurst* Signature: M Billinghurst Date: *26/7/2019*

Contents

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List of Abbreviations

AR	**A**ugmented **R**eality
ANOVA	**AN**alysis **O**f **VA**riance
ANS	**A**utonomic **N**ervous **S**ystem
BLE	**B**luetooth **L**ow **E**nergy
BVP	**B**lood **V**olume **P**ulse
BOOM	**B**inocular **O**mni-**O**rientation **M**onitor
CAVE	**C**ave **A**utomatic **V**irtual **E**nvironment
DES	**D**ifferential **E**motions **S**cale
EDA	**E**lectrodermal **A**ctivity
EEG	**Electroencephalogram**
FPS	**F**rames **P**er **S**econd
GSR	**G**alvanic **S**kin **R**esponse
GSR	**G**alvanic **S**kin **R**esponse
HMD	**H**ead **M**ounted **D**isplay
HCI	**H**uman-**C**omputer **I**nteraction
HR	**H**eart **R**ate
IAPS	**I**nternational **A**ffective **P**icture System
IADS	**I**nternational **A**ffective **D**igitized **S**ounds
LED	**L**ight-**E**mitting Diode
OS	**O**perating **S**ystems
PANAS	**P**ositive **A**nd **N**egative **A**ffect **S**chedule
PTSD	**Posttraumatic Stress Disorder**
RMSSD	**R**oot **M**ean **S**quare of the **S**uccessive **D**ifferences
STAI	**S**tate **T**rait **A**nxiety Inventory
SAM	**S**elf-**A**ssessment **M**anikin
SUD	**Subjective Units** of **Discomfort**
SD	**S**tandard **D**eviation
UDP	**U**ser **D**atagram **P**rotocol
UI	**U**ser **I**nterface
VR	**V**irtual **R**eality
VAS	**V**isual **A**nalogue **S**cale
VEs	**V**irtual **E**nvironments

Chapter 1

Introduction

Virtual Reality (VR) is a medium that immerses users in a computer-generated environment and can provide multi-sensory (audio, visual, and haptic) feedback [110]. With the help of digital environments generated by computers, users can experience and interact with virtual objects within the computer-generated environment as if the virtual objects were in the real world [57]. The ideal VR system is the one in which the users can be completely immersed, walking around and physically interacting with the objects in the Virtual Environment (VE) [114].

In the last few decades, researchers have investigated the immersive properties of VR and found that it can provide a "sense of being there" [110]. This perceived closeness, or the feeling of being there, has been labelled as "Presence" [69, 7, 99, 1, 117]. Further research demonstrated that VEs could be used to induce emotions in users [99, 1, 6]. Different subjective and objective measures, such as surveys, questionnaires, Heart Rate (HR), Galvanic Skin Response (GSR) etc, were used to measure emotions in a VE.

However, while previous researches have focused on creating and measuring emotions in VR, little work has been done to investigate the effects of providing physiological feedback to users in VEs and measuring their effects on emotions and interaction. Whether displaying a user's physiological state in VR or sharing physiological data with others in a multi-person VE has the potential to benefit users by providing a sense of self-awareness and the possibility to evoke empathy amongst users of a shared VE.

1.1 Motivation

Researchers have hypothesized that the emotions elicited in the real world can be evoked in a similar VE. For example, Riva et al. [99] used a VE comprising of trees, lamps, a bandstand and a summer cinema, and showed that adding varied music, sounds, lighting, shadows and textures could evoke different emotional responses in participants. Seinfeld et al. [106] designed a VE with an exterior exposed elevator in a 350m building to evoke anxiety associated with ascending and descending great heights. The subjective and objective results of this study demonstrated that emotions felt during ascending and descending in the elevator were significantly different than those felt on the ground. Felnhofer et al. [36] designed replicas of real-world parks in VR with different emotional triggers like trees shown in different seasons and various lighting effects to evoke the target emotions.

Thomas writes, referring to VR, that “Perhaps the most profound long term applications, however, of such technologies may be as an empathy machine” [115]. He further describes how in the future it might be possible for VR to give one person the feeling of being someone else. Billinghurst et al. explored the use of Augmented Reality (AR) and VR to convey emotional states and so allow users to capture and share their emotional experiences [91, 11]. He named this field of research “Empathic Computing” and defined it as researching computer systems that create deeper understanding or empathy between people [11] and further explained that “Empathic Computing requires a combination of rich natural collaboration, capturing the user experience and surroundings, and being able to implicitly understand user emotion and context”, as illustrated in Figure 1.1. Billinghurst et al. [11] describes the empathic computing system has three types, namely understanding systems that can understand feelings and emotions, experiencing systems that put people into the recorded world of others and sharing systems that share the real-time experience of others. The work conducted by Dey et al. involved sharing real-time HR information of the player with an observer in a VR gaming scenario. The study found positive effects of sharing HR data [29]. In the study, the observer was a passive viewer while the player performed all of the interactions. However, the study was asymmetrical and did not involve the sharing of emotions amongst the two participants. There is relatively little research on how VR technology can be used to share the feelings or emotional states of one person to another in real time.

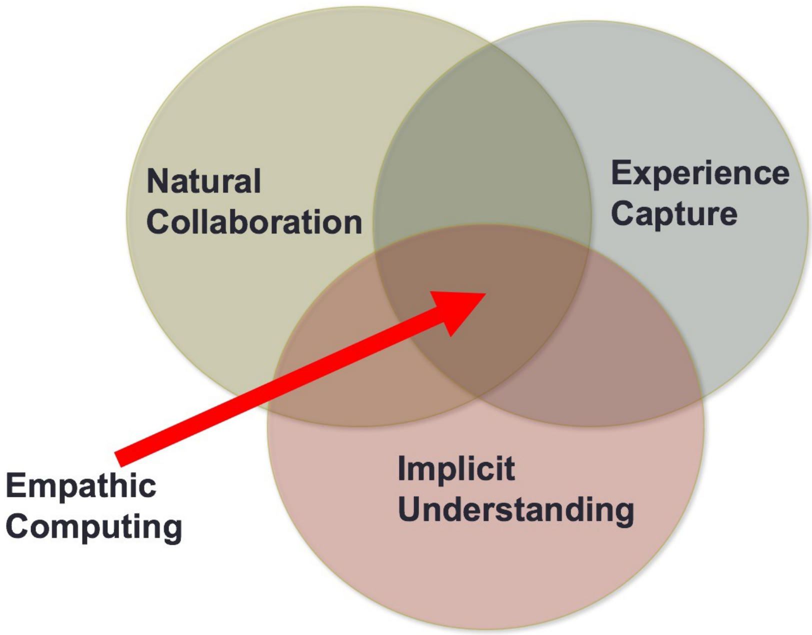

FIGURE 1.1: Empathic Computing, Combining Natural Collaboration, Rich Experience Capture and Implicit Understanding [11].

In the thesis, we share the physiological cue in different VEs mutually in users to investigate how users would respond to the physiological cues subjectively and objectively. Could these cues help users in VR notice the emotion states of others and could these cues help them to understand each other more in the collaboration tasks?

1.2 Research Questions

Based on the research that has been detailed in the last section, the following questions form the basis of my PhD research:

- Q1: Emotions in VR have been investigated for decades. What can I learn from the previous research to help my PhD research?

  - 1: What could be used in VR scene to evoke different emotions?
  - 2: What could I use to measure the emotions and what are the measurements used by previous researchers?
  - 3: What could I learn about sharing emotions from other platforms like desktops and mobile phones, considering little work has been investigated in VR?

- Q2: What is an effective way to convey and share emotion in users and could it help them notice their emotional state?
- Q3: How would the emotions of users change if the feedback is manipulated when they are in VEs, and would they notice that the feedback was being manipulated?
- Q4: Immersing in the same VE, when two users share emotions between them, how could they affect each other's emotion and how could the sharing of emotion impact the virtual experience of users?
- Q5: When users are sharing emotional states in VR, how would they respond to the manipulated emotional cues?
- Q6: Are there some effective objective measurements of emotion that could be used in VR?

1.3 Findings and Contributions

The work presented in this thesis makes significant contributions to the use of physiological measurements in VR in terms of user emotion. It demonstrates the effectiveness of sharing physiological data in VR. In particular, three important findings and contributions from this thesis are:

(a) In the multi-sensory feedback of HR, we design five feedback conditions and validate the haptic and audio feedback is preferred compared to the visual symbol in VR. Imposing the manipulated Haptic-Audio HR feedback on subjects in Chapter 4, we find some emotions could be affected by the manipulation feedback. For example, the manipulation of +15% HR feedback made subjects more nervous and scared than -30% feedback.

(b) Sharing of physiological data can have a positive impact on shared experiences in VR. The studies in Chapter 5 and Chapter 6 demonstrate that users experience higher levels of Social Presence when physiological data is shared amongst participants in the same VE and they feel more connected and could notice the changes of some emotions compared to the situation of no physiological cue in the VEs.

(c) In Chapter 7, we implement the first prototype integrating the pupil dilation sensor and the photo sensor into the HMD. The photo sensor could help compensate the pupil dilation caused by the brightness in the HMD when we measure the pupil dilation caused by the stimuli in the VEs and this prototype could be used potentially to measure emotions in VEs. In the study using this prototype, we find the emotions VEs could increase the pupil dilation compared to the baseline.

1.4 The Structure of the Thesis

During my PhD, I conducted five studies to address the questions in Session 1.2 and all experiments were approved by the human ethics committee of the University of South Australia. This thesis is structured as follows.

Chapter 2 addresses question 1 and its sub-questions. This chapter first briefly goes through the VR history, presents the highlights of VR technology and the VR pioneers who made major contributions to VR research. In later sub-sections, a literature review of emotion-related research in VR is provided, highlighting VE design techniques used to evoke emotions, like lights, sounds, zombie attacks, etc. The last part of the chapter covers the research on sharing emotions via physiological signal cues in different platforms. HR was found to be used the most in previous emotion-sharing research.

Chapter 3 addresses question 2. In Chapter 2, I reviewed previous research using HR as biofeedback to share emotions. However, there is no consistent method for representing HR feedback in these studies. Some research used visual-audio feedback, some used haptic feedback and some only used audio feedback or only used visual feedback. From the literature review, I cannot get an answer to question 2. Then five VR emotional experiences were designed in my first user study. Four different Multi-Sensory HR Feedback conditions (audio-Visual, audio-haptic, visual-haptic and audio-visual-haptic) were investigated in the study. We found that audio-haptic feedback was the most preferred and users could effectively notice their HR using audio-haptic feedback.

Chapter 4 addresses question 3. We systematically investigated the emotional and physiological effects of providing manipulated HR feedback to users, in decreased, increased, and non-manipulated ways, when they were experiencing different VR scenarios. We used the audio-haptic feedback of the real-time HR of users, which has been identified as the preferred feedback from the last study in Chapter 3. We measure which emotions can be altered and how real physiological signals were affected by this modulation. Subjective measurements have been the primary mode of investigating emotions in VR, but the physiological measurement also was used. This work was to examine how additional physiological feedback, on top of traditional audio-visual effects in VR, can affect the overall experience, and whether or not some specific emotions can be enhanced or reduced by manipulating the feedback.

Chapter 5 addresses question 4 Keeping in mind that my research topic is sharing emotions in VR, in previous chapters, we investigated how emotions could be conveyed to the user by using audio-haptic feedback. In order to investigate more on sharing emotions between users, in this chapter, three new VEs were designed. In the study, users were in the same VE and physiological feedback, such as HR, was shared between the users. Through a user experiment, we evaluated how providing HR feedback to collaborators influenced their collaboration in three environments requiring different kinds of collaboration. We found that when provided with real-time HR feedback participants felt the presence of the collaborator more and that they better understood their collaborator's emotional state. HR feedback also made participants feel more dominant when they were performing the tasks.

Chapter 6 addresses question 5 In Chapter 6, we investigated a study where a collaborator's HR feedback was shared with another collaborator in a VE in a modified form. In the study, six VR scenes were designed. Three of them were passive games and the other three VR scenes were active. In the VR environment, users could hear the other person's heartbeat. In order to address question 5, we designed three levels of modification (-20%, 0% (real), and $+20\%$) according to what we have learned in the study in Chapter 4. From the results, we found that nervousness and scariness in the VEs can be manipulated by providing manipulated HR feedback of one collaborator to the other.

Chapter 7 addresses question 6 Emotion is manifested through the Autonomic Nervous System (ANS) and changes in physiological cues such as GSR, facial expression, HR, body temperature, and pupil dilation. In the previous VR research, HR and GSR were used to measure emotion. However, to my best of knowledge, there is no research on using pupil dilation to measure emotions in VR. In this chapter, we investigated the pupil variation by using positive or negative affective VR scenes. We found that the pupil diameters increased in both positive and negative emotional segments. We noticed that visual-haptic feedback increased the pupil diameter the highest among all conditions, while not having any feedback caused the least pupil dilation. It is clear from the results that pupil dilation is effected by VR environments. But more studies would be needed to establish the relationship between pupil dilation and emotional arousal in VR.

Following the studies, Chapters 8 covers the discussions and conclusions arising from this thesis. We also present future work that can be carried out to further the research that has been detailed in the thesis.

Chapter 2

Background

In the previous chapter, the motivations behind the research were introduced and the questions that the research is aiming to address in the thesis were covered. This chapter introduces the previous work that has already been investigated by researchers. Also, this chapter will briefly introduce the history of VR.

2.1 A Brief History of Virtual Reality

The term "Virtual Reality" was coined by Jaron Lanier in 1985, but the research of VR started much earlier. In 1832, Charles Wheatstone invented a device called a Stereoscope, as shown in Figure 2.1. The device had mirrors angled at $45°$ which reflected images into the eyes from the left and right side [57]. Later, David Brewster invented a hand-held stereoscope with lenses (Figure 2.2). The stereoscope was exhibited in an exhibition in 1851. In 1895, a device called Haunted Swing with a $360°$ VR-type display was exhibited at the '95 Midwinter Fair in San Francisco [133].

In the 1900s, VR-related research moved from not only presenting the visual images but also adding interaction techniques delivered on systems like today's head-mounted display (HMD). In 1916, Albert Pratt patented a head-worn gun pointing and firing device, as shown in Figure 2.3. The device had no hand tracking interface but there was a tube which users could blow through to fire [93]. In 1928, Edwin Link built a simple mechanical flight simulator for the military, as shown in Figure 2.4. The simulator had a cockpit

FIGURE 2.1: Stereoscope invented by Charles Wheatstone [57]

FIGURE 2.2: A Brewster stereoscope from 1960 [57]

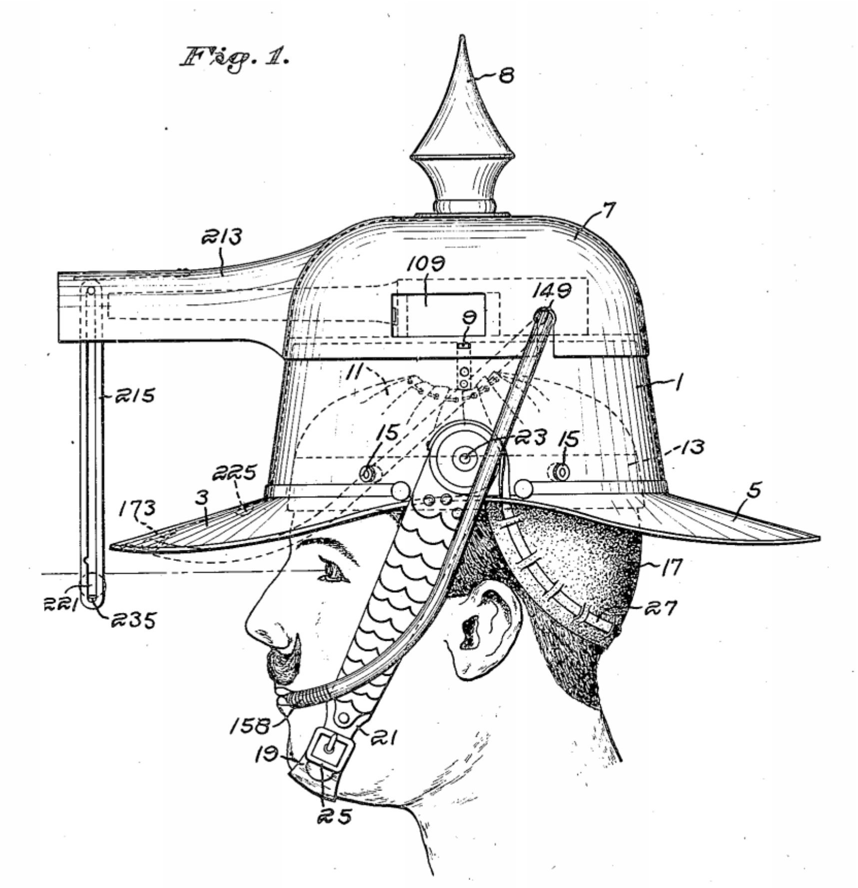

FIGURE 2.3: Albert Pratt's gun-firing system [93]

and controls which could produce motions and a flying sensation. In the 1950s, Morton Heilig designed both an HMD and a world-fixed display [57]. Figure 2.6 shows the HMD created and patented by Heilig. It had lenses that enabled a 140° horizontal and vertical field of view, stereo earphones, and air discharge nozzles that provided a sense of breezes at different temperatures as well as scent [57]. The world-fixed display designed by Heilig was called Sensorama, as shown in Figure 2.7. The Sensorama system was created for immersive film and it provided stereoscopic colour views with a wide field of view, stereo sounds, seat tilting, vibrations, smell, and wind sensations [51].

Philco Corporation engineers, in 1961, developed the first tracked HMD, as shown in Figure 2.5. When users wearing the HMD moved their head, a camera in a different room moved so that the users could see as if they were at the other location [57]. In 1965, Tom Furness and others at the Wright-Patterson Air Force Base started working on HMD systems for pilots. The

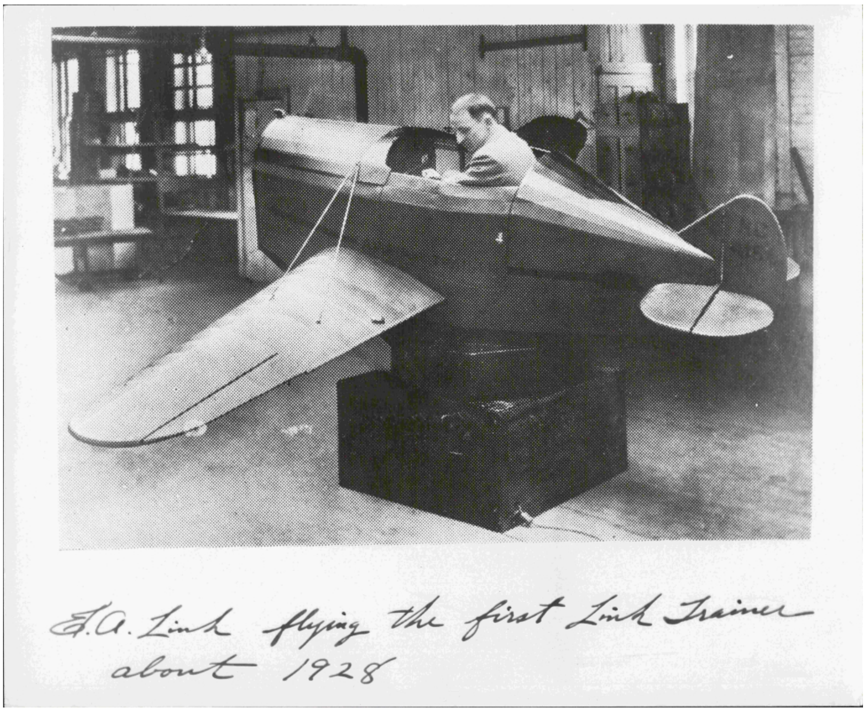

FIGURE 2.4: Edwin Link's first flight simulator in 1928 [120]

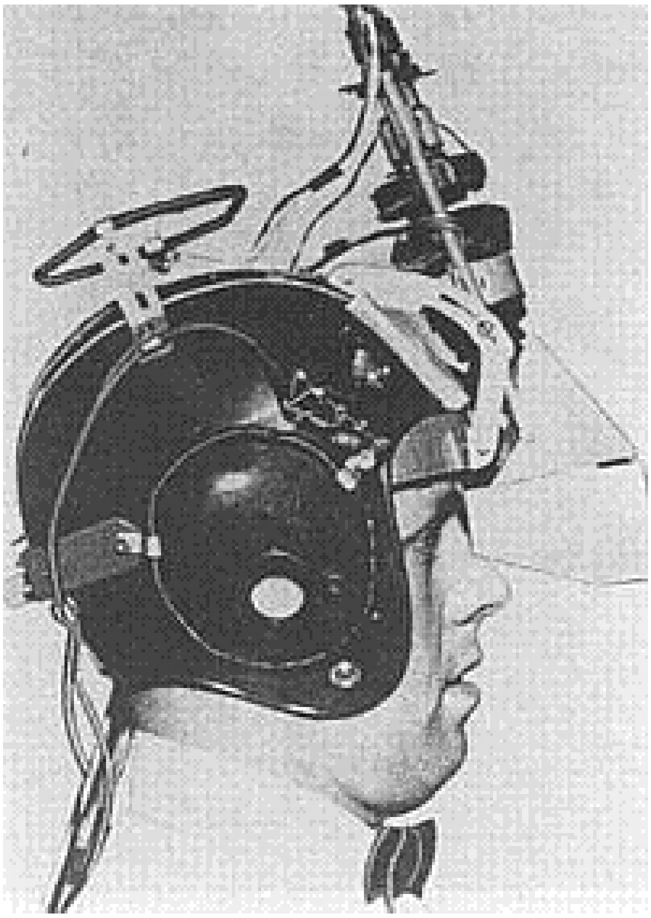

FIGURE 2.5: The Philco Headsight from 1961 [22]

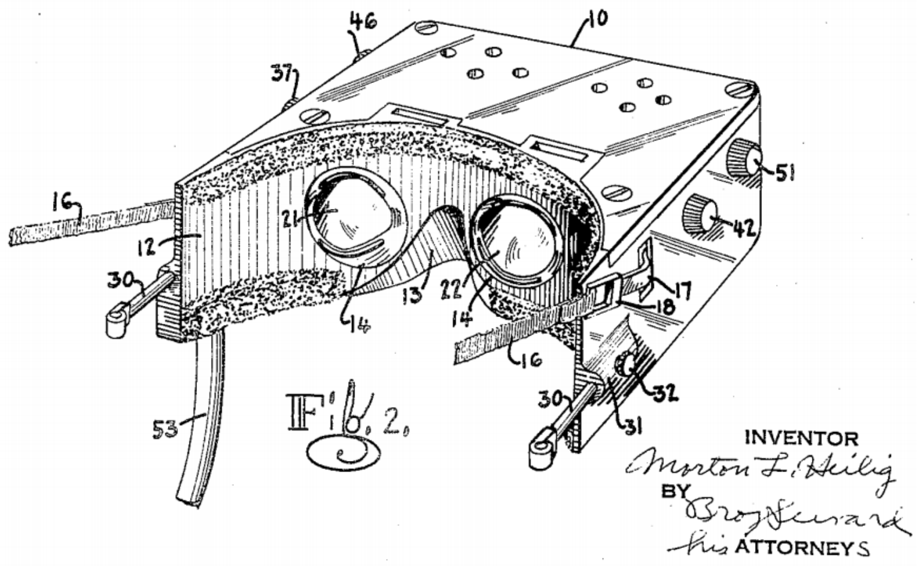

FIGURE 2.6: A Stereoscopic-television apparatus patented by Heilig in 1960 [50]

HMD designed by them is shown in Figure 2.8. Ivan Sutherland was doing the similar work as Furness at Harvard and the University of Utah at that time and he and his student Bob Sproull demonstrated the first HMD with head tracking and computer-generated images [84]. The system used a mechanical tracking system called 'The Sword of Damocles' (Figure 2.9), named after King Damocles who had a sword hanging above his head by a single hair.

In 1985, Scott Fisher, at NASA Ames, created the Virtual Visual Environment Display (VIVED) (Figure 2.11, left) system with other NASA researchers. This HMD was known as to be the first commercially viable and stereoscopic head-tracked HMD [38]. It had an effective field of view for each eye of $120°$ horizontal and $90°$ vertical. The displays had two Citizen Pocket TVs [57]. Later a system called the Virtual Interface Environment Workstation (VIEW) system was built, as shown in Figure 2.11, right. In 1985, Jaron Lanier and Thomas Zimmerman started Visual Programming Language (VPL) Research and they built commercial VR gloves and HMDs.

In 1989, the Fake Space Labs commercialized Binocular Omni-Orientation Monitor (BOOM) which was a small box mounted on a jointed mechanical

FIGURE 2.7: The Sensorama system created by Heilig in 1962 [49]

FIGURE 2.8: The Wright-Patterson Air Force Base HMD from 1967 [57]

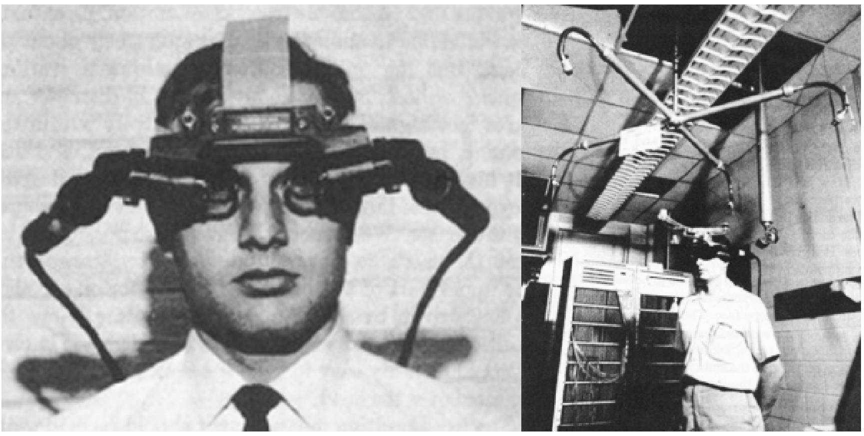

FIGURE 2.9: Sutherland and The Sword of Damocles [57]

FIGURE 2.10: A Binocular Omni-Orientation Monitor (BOOM) [86]

arm with tracking sensors located at the joints [86], as shown in Figure 2.10. To view the virtual environment, the users need to hold the box and kept it by the eyes. By moving the position and orientation of the joints on the mechanical arm, users could feel the movement in the virtual world [75].

In the 1990s, companies were mostly focusing on the market and entertainment. Jonathan Waldern established a VR company named Virtuality[1] [121]. The company focused on putting VR system into gaming arcades and built several arcade VR systems [121]. One of them is shown in Figure 2.12. VR

[1] https://en.wikipedia.org/wiki/Virtuality$_{(gaming)}$

movies were produced, such as Brainscan, Arcade, and The Thirteenth Floor, etc. [123]. Many books were written and conferences were formed on VR as well [57]. In 1993, Wired magazine predicted that more than one in ten people would wear HMDs during travelling in the next five years [83]. However, 1996 saw the peak of VR industry, and after this VR companies went out of business slowly, including Virtuality.

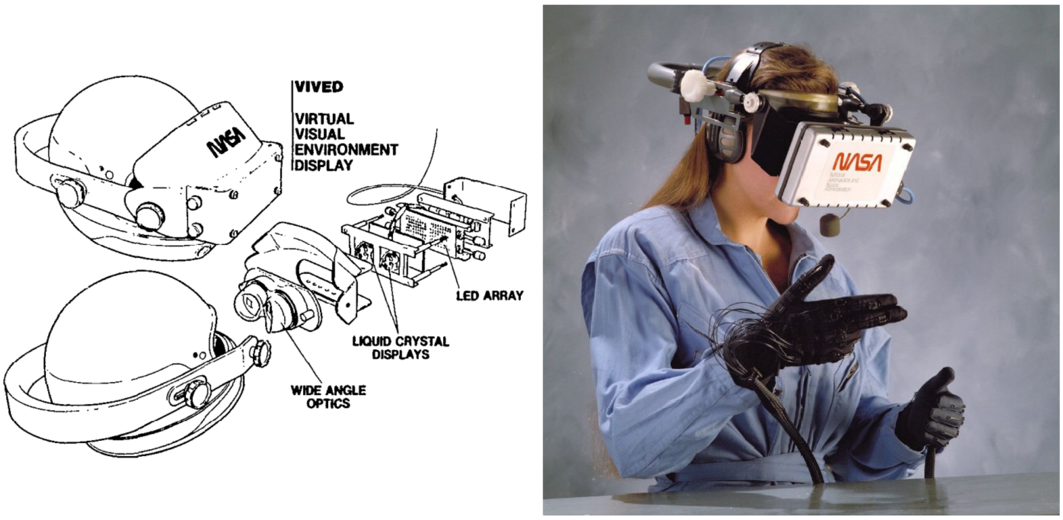

FIGURE 2.11: VIVED System (Left) [38] and VIEW System (Right) [57]

FIGURE 2.12: One arcade VR system from Virtuality [121]

In 1992, Carolina Cruz-Neira [18], Daniel J. Sandin [25], and Thomas A. DeFanti [116] invented a new VR interface called Cave Automatic Virtual Environment (CAVE) at the University of Illinois, Chicago Electronic Visualization Laboratory [75]. Instead of using HMD, the system projected stereoscopic images on the walls of room [24], shown in Figure 2.13. The user wore shutter glasses inside the CAVE to see 3D graphics generated by the CAVE.

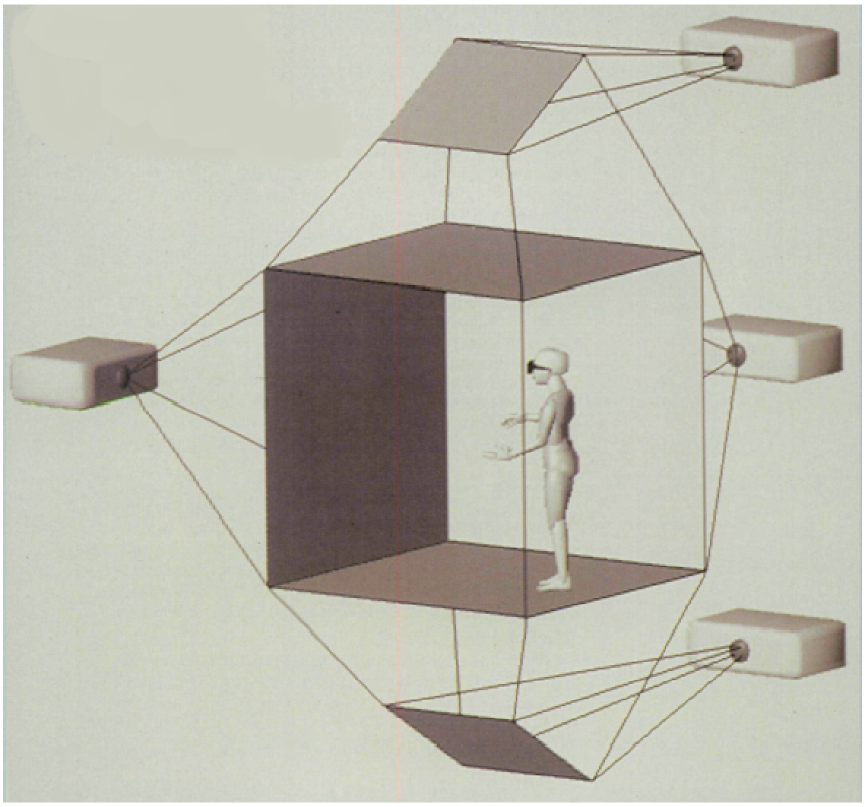

FIGURE 2.13: Cave Automatic Virtual Environment (CAVE) system [24]

In the 2000s, VR experienced a "winter" after the explosion in the 1990s, and little mainstream media attention was given to VR in the first decade of the 21st century. However, at that time VR research still continued in academic, military, corporate, and government research laboratories, etc. VR research started to be turned to human-centred design with more user study evaluations [57].

In 2006, Mark Bolas in USC's MxR Lab and Ian McDowall in Fakespace Labs created an HMD with a 150° field of view named The Wide5, as shown in Figure 2.15. The lab used this HMD to study user behaviour and experience with a wide field of view HMD and they found that users could judge the distance more accurately in a larger field of view when they were walking to a target in VR [58]. Later the team developed a low-cost VR device called the Field of View To Go (FOV2GO) (Figure 2.14). The device was demoed in the IEEE VR 2012 conference and won the best demo award that year. It

FIGURE 2.14: The Field of View To Go (FOV2GO) [113]

was also an open-source project from MxR Lab and was considered as the precursor of current consumer mobile VR HMDs [57]. Palmer Luckey from the lab later founded Oculus VR with John Carmack and launched the Oculus Rift Kickstarter campaign in 2012 to fund the Oculus Rift HMD.

FIGURE 2.15: The Wide5 HMD from Fakespace labs [130]

Overall, the VR technology has been developed for decades. Currently, affordable commercial HMDs with high quality are available. Figure 2.16

shows some VR HMDs in the market from different companies. Some of them integrate some new features into the HMD, such as the VR headset from Looxid Labs with eye trackers and EEG physiological sensors. Also, the high-resolution HMDs are available, like PIMAX version 8k VR headset. Schubert et al. [105] mentioned that high qualification of the VR equipment could help the immersion and presence in users in the anxiety-provoking virtual environments. With the advanced technology, the research of emotions in VR will be benefited as well. In the next session, we will review the previous work on the emotions in VR.

FIGURE 2.16: Commercial HMDs available from different companies (Oculus rift [85], HTC Vive [54], Sony PlayStation VR [109], ‘ Google Daydream View [46], Looxid [70], PIMAX [87])

2.2 Emotion in the VR Experience

VR is described as being able to create a "perceptual illusion of non-mediation" in users [6, 7, 99]. Users without noticing the medium created by technology would behave, think and feel in VR just like they would in the corresponding real world. How they respond to emotional stimulus in VEs is an area of research that has garnered significant attention in recent years. While some investigation has been conducted in the area, knowledge in this field is still quite limited. The use of subjective and objective measurements of emotion in several studies have found that subjective measurements provide more consistent results [76, 33, 77].

2.2.1 Previous Investigation on Emotions in VR

Emotions acting as ubiquitous affective states in the social and behavioural world have been researched in VEs. Previous researchers like Felnhofer, Riva, Banos etc. hypothesized that emotions elicited in the real world could be provoked in the corresponding VEs [36, 34, 99, 6].

Riva et al. [99] compared two emotional VEs, relaxing versus anxious virtual parks along with a neutral VE as a control condition. They tried to analyse the possibility of using VEs as an affective medium, like music and film, which have been shown to possess the capability to induce emotions [59, 64, 112]. The three VEs in his study shared the same park structure, including trees, summer cinema, lamps and bandstand but the sound and music, shadows, lights and textures were altered in different VE. In the user study, the three conditions were randomized and all the participants experienced all the conditions. Participants filled presence and emotions questionnaires after each condition. An analysis found that after exposure to the anxious VE, the happiness and positive affects were reduced and sadness and anxiety were increased. The opposite was true for the relaxing VE, while the neutral was shown to have no significant impact on the emotional state. From the results of Presence questionnaires, it was shown that the emotional VEs scored much higher than the neutral VE.

Felnhofer et al. [36] expanded her research into five emotions: joy, boredom, anger, sadness and anxiety. In her study, each participant experienced one of the five emotional VEs. In the five emotional VEs, four of them, except the virtual park of boredom, shared the same virtual park scenario with different sounds and lighting conditions as emotional stimuli. In order to obtain comprehensive measures, subjective measurements were taken after exposure to the VEs. The objective measurement in the form of Electrodermal Activity (EDA) was used as well. Results showed that joy, anger and anxiety emotions could be elicited by the corresponding emotional VEs while the boredom and sadness VEs did not produce conclusive results. The objective measurement did not show statistically significant differences amongst the five emotional VEs.

Project EMMA (IST-2001-39192) [1] studied whether emotional states could be induced based on the positive or negative virtual experiences participants experienced. Based on the framework of the EMMA project, five emotions, including sadness, joy, anxiety, relaxation and neutralness, were involved in the study [7]. Based on the analysis, it was observed that happiness and relaxation VEs scored higher in joy, followed by the neutral one. The anxiety and sadness groups, on the other hand, induced a sadder mood than the happiness, relaxation and neutral VEs.

Banos et al. [8] investigated whether positive emotions could be induced in elderly people after exposure to the positive emotional VEs. In the user study, two emotional virtual parks (relaxation and joy) were designed. From the results, they found an increase in the positive emotions among the elderly. They also showed a reduction of positive emotion when exposed to the negative VEs.

A neutral virtual setting on a terrace with tables and chairs was designed by Seinfeld et al. to measure the baseline emotional response in comparison to that elicited by an exterior elevator platform on a 350m tall building [106]. The ascending and descending experience on the platform was supposed to elicit anxiety. Both subjective and objective measurements were utilized to measure anxiety. The results showed that participants on the higher virtual floors were experiencing stronger levels of anxiety than when they were on the lower floors.

Regenbrecht et al. [96] designed a virtual environment with cliffs, shown in the Figure 2.17. At the beginning of the study, the floor did not have cliffs for subjects to get used to the VE and subjects could walk around without any tasks. After the given time, some parts of the floor were lower down 8 meters to form the cliffs. After that, the subjects had to find texts of instructions to finish tasks in the virtual world. The instruction was formulated so that the subjects had to move around near the cliffs. Also, the height of cliffs was shown in the VEs. The results of a self-report questionnaire about anxiety showed that the subject had fear emotion when subjects were exposed to the cliffs.

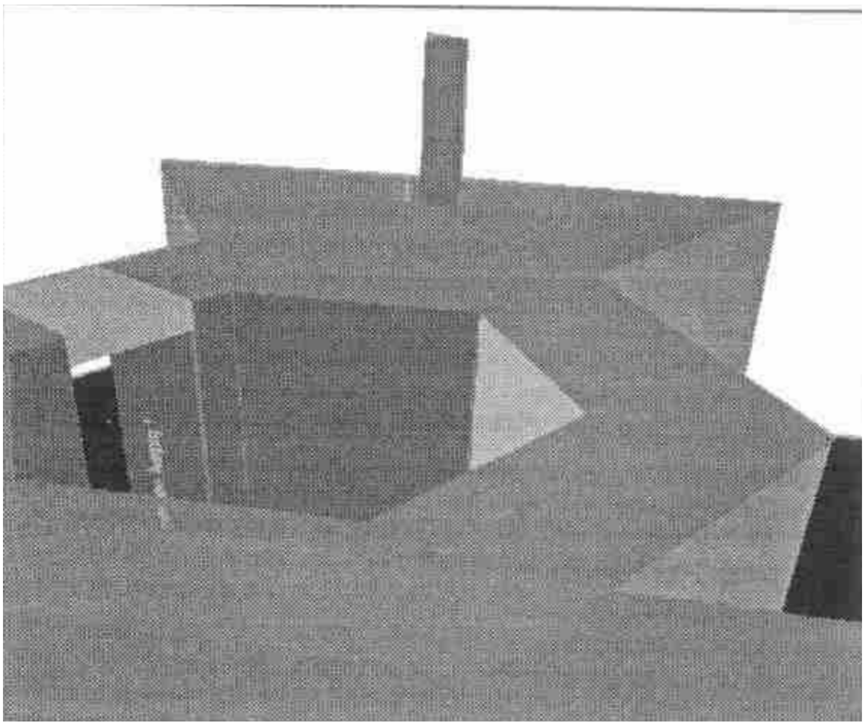

FIGURE 2.17: A Virtual Environment with cliffs [96]

VR also was used as treatments of phobias in the last decades. Carlin et al. [17] used virtual environments to treat the spider phobia. In their study, subjects weekly conducted 50 minutes treatment when wearing the HMD and the treatment lasted for three months. During the treatment, the subjects' anxiety level was assessed in each minute after the exposure. From the result, it showed that in the virtual world, the subjects kept high anxiety when they saw the virtual spiders and interacted with the spiders. Garcia et al. [40] investigated a similar study in the spider phobia treatment. In their treatment, the patients were asked to touch and hold a virtual spider in the virtual environment, and the tactile feedback was utilized. The patients felt anxiety in the entire treatment even though the virtual environment was exposed to them repeatedly and the tactile feedback augmented the anxiety.

Rothbaum al et. [101] used VEs to examine the efficacy of VR exposure on the fear of flying. They treated a female patient who worried about the plane crashing and feared the flying of vacations for five years. In the VR exposure, the subject was sitting in a virtual aeroplane, experiencing the takeoffs and landing. During the flying, both calm and stormy weather were simulated in the virtual environment. The audio of takeoffs, landings, storms and thunders were provided to the subject via a headphone. The treatment had six sessions and lasted for approximately 35∼45 minutes. From the results, the subject could be triggered to be more anxious compared to the pre-treatment phase. In the session of turbulence and thunder, the subject had the highest score in anxiety.

Klinger et al. [63] created four virtual environments including situations dealing with social anxiety: performance, intimacy, scrutiny, and assertiveness. In the study, 36 participants diagnosed with social phobia were recruited. In the four situations, the subjects would finish different tasks, for example, in the performance situation, the subjects should speak in front of audiences in the virtual environment. The four situations were supposed to evoke performance anxiety, intimacy anxiety, scrutiny anxiety and assertive anxiety, respectively. The results showed that the treatments could help reduce anxiety.

Rothbaum used VR exposure to treat Posttraumatic Stress Disorder (PTSD) in his research. They investigated the VR exposure to the Vietnam veterans who suffered from chronic combat-related PTSD [102]. The subject in the treatment was a helicopter pilot serving in Vietnam. During the treatment, the subject was exposed to virtual environments with audio and visual effects. The audio included recordings of gunfire, helicopters, mine explosions, etc. and visual effects had muzzle flashes from the jungle, helicopters flying overhead, landing and taking off etc. Another study in [42] showed that a veteran who served in Iraq before can trigger fear emotion when he was convoying two soldiers who were attacked in the virtual environment with the landscape of the desert.

Krijn et al. [65] designed four VEs with different heights, including a shopping mall with four floors, a fire escape with six floors in open space, a roof garden on a building and a virtual building site with eight floors for the treatment of acrophobia. The subjects were exposed to each EV for ten minutes and after each exposure, subjects would rate their anxiety by means of Subjective Units of Discomfort(SUD). The results showed that all the VEs provoked more anxiety in subjects than no treatment condition. Muhlberge et al. [81] conducted a study on the fear of flying. After relaxation training, subjects took the exposure of 16 minutes to a virtual flight. The results of SUDS, HR and GSR showed that the height of virtual flight was able to elicit fear responses in phobics.

2.3 Emotion Sharing via Sharing Physiological Signals Cues

People are quite used to communicating via text message using a mobile phone. Often, emojis are sent during the chat but people still suffer from the lack of understanding of the context and emotion awareness [30]. Some researchers have investigated means of sharing emotions between users. Hassib et al. [48] designed a chat application for the mobile phone called HeartChat which integrated an HR cue into textual communication. From the results of their study, they found that HeartChat supports awareness and empathy between interlocutors, acts as a context cue, and promotes engagement and play in the chat activity. In an exploratory study, Gijsbrechtes et al. [44] tried to explore the empathy between the users when they were sharing social video clips by sharing their HR reaction to the videos on the mobile phone. Lee et al. [68] integrated two physiological activity metrics, Blood Volume Pulse (BVP) and GSR, in a chatting system named "Empa Talk". In the system, a vibrator and an RGB LED were also used to convey and display the physiological data on each other’s wrists. From their pilot study of five participants,

FIGURE 2.18: HR data displayed on the helmet of bicyclist (left) and the chest-worn sensor streaming HR data to the helmet display, which was viewed by other cyclists (right) [125]

they found that chatting integrated physiological data could help subjects engaged more in their communication by perceiving the other user's emotional status.

Physiological signals were also shared in a range of different activities. For example, Crumi et al. [21] shared real-time HR data in a sport event. They designed a system called HeartLink, which could collect the HR from athletes during the sports events and broadcast to viewers in real time. In their pilot study, conducted with athletes in a charity run, HR was visualised and shown on a social network. The viewer felt much closer to the participants even though they were separated geographically. On the other hand, the participants could be more motivated because of the feeling of "being followed". In a bicycle helmet designed by Walmink et al. [125] for displaying HR data, it was observed that when this data was presented to other cyclists, they reported it helped increase engagement with one another. Another interesting fact was that the participants reported that individual goals rapidly morphed into shared team goals when viewing the HR of another cyclist on the team.

There are also a few recent examples of sharing physiological data in VR. Dey et al. [29] designed a collaborative system in VR that had two environments: butterfly collection and a zombie shooting game. The system is shown in Figure 2.19. During the user study, one subject played the games (shooting zombies and collecting as many butterflies as possible in the fixed time) and the other subject was an observer, watching the game player's actions and

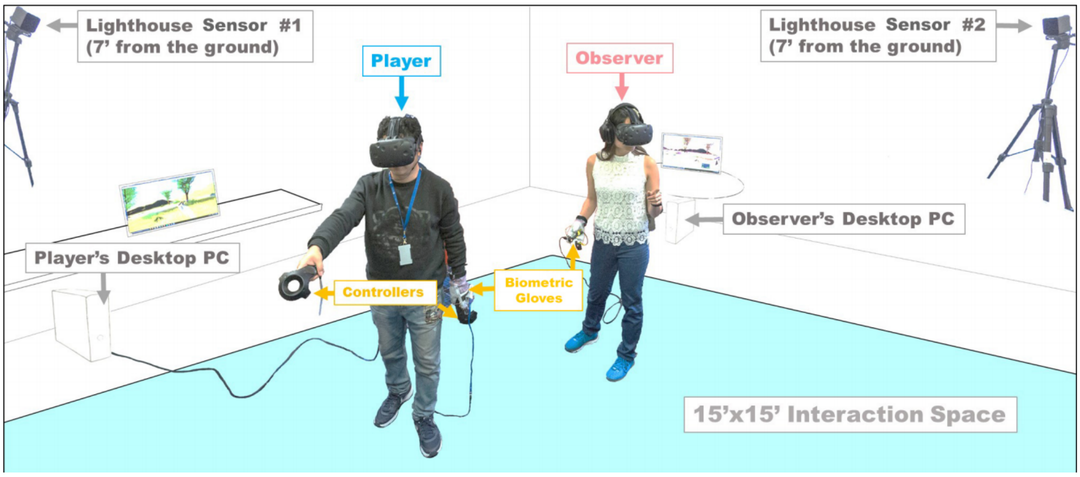

FIGURE 2.19: The system shares player's HR to the observer in VR game [29]
.

his or her surroundings and talking to the player about their situation, for example alerting them with statements such as "A zombie is coming to attack you from behind." They were both in the same VE. In the game, HR of the player was shared with the observer. The results found that HR of player was able to elicit a more empathic response from the observer, making the collaboration seem more natural and intuitive.

Ueoka et al. [118] designed a VR system called Emotion Hacking VR (EH-VR), as shown in Figure 2.21. Users put their feet on a wood plate while wearing an Oculus Rift HMD and at the same time, a manipulated vibrotactile heartbeat was given through the sole of the feet gradually accelerating its frequency. The results showed that the participant's heartbeat was increased by about 20 beats per minute compared to the baseline.

Ando et al. [2] designed a system called "Empathetic heartbeat". In their study, the participants were listening to their heartbeat when they watched the video clips with nervous people, such as children before running in a race and soldiers in a battle field [2]. They found sharing the heartbeat could help participants understand the emotional states of people in the video.

Also, there is some research sharing experience in VR via haptic feedback. Mizushina et al. [79] designed a system recording sports play with

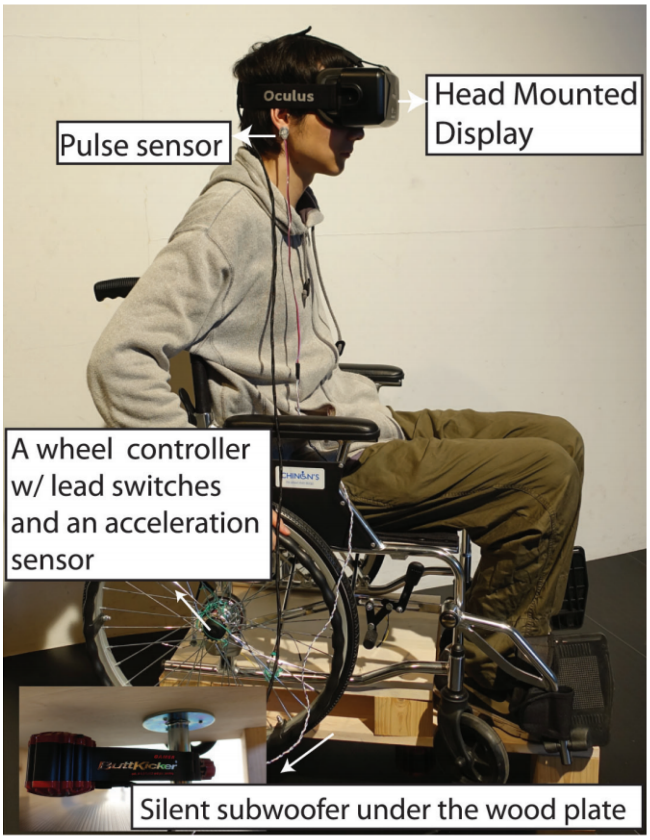

FIGURE 2.20: Prototype system of EH-VR [118]

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FIGURE 2.21: Empathic heartbeat [2]

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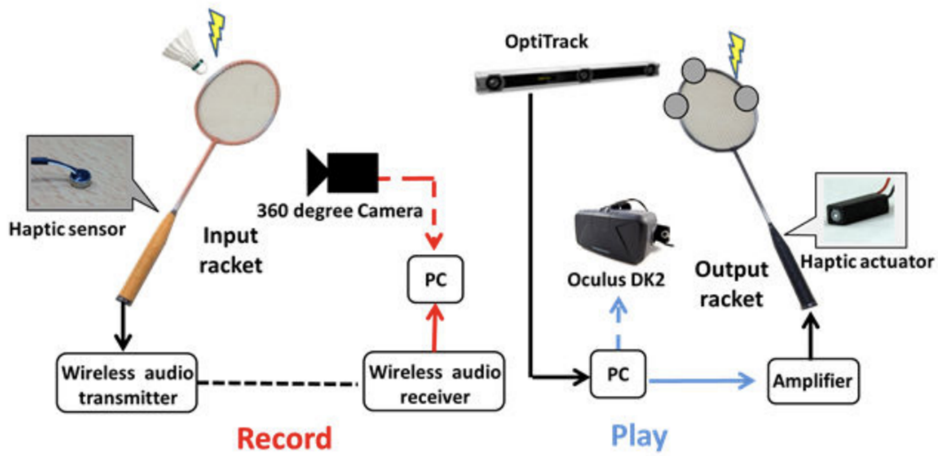

FIGURE 2.22: Interactive Instant Replay system [79]

360-degrees spherical images and haptic sensation and sharing the sport experience to others, as shown in Figure 2.22. They named it “Interactive Instant Replay” system. In the system, the users could experience the first-person view recorded from others when they wore an HMD. Also, the haptic racket in their hand could generate the haptic sensation when the users interacted with the badminton in the virtual world. Maeda et al. [71] designed a wearable system that enhances haptic sensation called HapticAid. The system has a wearable skin vibration sensor at the middle phalanx of a finger, a processor processing haptic information, and a wrist-worn haptic actuator, as shown in Figure 2.23. Using this system, they try to communicate and share the haptic experiences. For example, the haptic sensations previously recorded are played back for other participants. Also, participants exchange haptic sensations with others when wearing an HMD.

2.3.1 Conclusion

In this chapter, we have gone through a brief history of VR and the important stages of VR development. In the next section, the previous research of emotions in VR was reviewed and we also covered sharing physiological signals on different platforms, such as mobile phones, desktop and VR headsets.

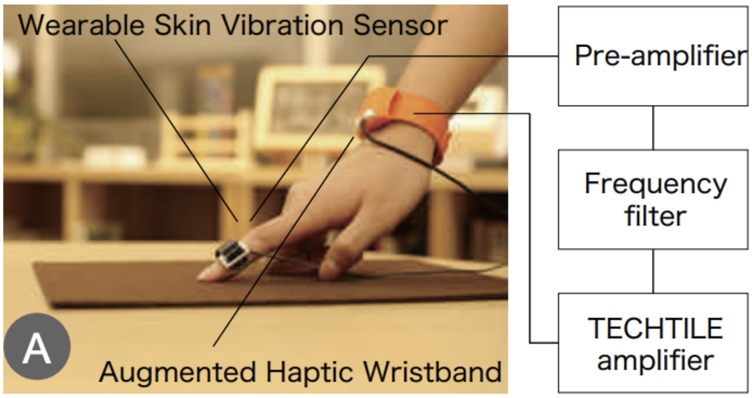

FIGURE 2.23: HapticAid system [71]

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From the previous research on emotions in VR, we know VEs can evoke emotions. From the research on sharing physiological signals in other platforms, we know that sharing physiological signal cues between users could help them understand each other's emotional states and also increase connectivity and in turn enhance the sense of empathy for one another. However, the research on sharing emotions in VR has not been investigated. In the next chapters, we explore the research of sharing emotional states via sharing physiological signals in a variety of VEs, including passive VR experience and interactive VE.

Chapter 3

Exploring the Design Space of Multi-sensory HR Feedback in Immersive VR

The first experiment we conducted was to investigate which type of multi-sensory feedback was the one preferred by users in VEs. In the experiment, four different multi-sensory feedback conditions (audio-Visual, audio-haptic, visual-haptic and audio-visual-haptic) were designed and data from users were collected and analysed. This study was presented as a full paper in the 29th Australian Conference on Human-Computer Interaction (ozCHI'17) which was held in Brisbane, Australia from 28th November to 1st December 2017.

3.1 Introduction

As we have already seen in Chapter 2, there have been some previous efforts at using VR experiences for evoking and measuring emotions. However, the effect of showing the user his or her own emotional state in a VR environment has not been extensively researched. Dey et al. [29] found the HR of a remote collaborator was displayed to a VR user to make the collaboration more empathic. However, in that work the authors only used a single type of audio-visual feedback to display the user's HR. Bernal and Maes [10] developed a system to express emotions using avatars in a virtual environment.

The user's GSR and HR physiological signals were captured and a neural network was used to estimate four emotions from the raw GSR and HR data. They represented emotions visually in two different ways: (1) the hair on the skin of avatar (growing when the arousal was high) and (2) intensifying the brightness or changing the avatar colour when the user is in a high arousal situation. The system was designed using an open-source VR system called PhysioVR [82]. Visualizing physiological data in a collaborative video conferencing was investigated by Tan et al. [111]. Both HR and GSR were shared to the participants in the monitor. They found these physiological cues significantly reduced the stress and the mental workload of participants.

So there is a need to understand how to represent physiological states for maximum effect in VEs, which will enable VR researchers to create more empathic VR experiences. By making VR systems more empathic they can be used for various training and teaching purposes [43]. An empathic VR system could also help treat phobias and disorders [41], and there are many other potential application areas. In the research in this chapter, we systematically measured the real-time HR of VR users and presented it using four different multi-sensory combinations, namely **audio-visual, audio-haptic, visual-haptic and audio-visual-haptic**. While the benefits of multi-sensory feedback for general interactions in VR has been established by earlier work [37], that effect has not been studied adequately for providing physiological feedback.

3.2 Virtual Reality Experiences

For the study, five different VR test experiences were developed using the Unity 3D game engine[1]. Each of the environments was carefully designed and validated to evoke similar experiences in the same order and for equal amounts of time. We primarily focused on five different emotions—happiness, anxiety, fear, disgust, and sadness (Figure 3.1). The VR experience involved

[1] https://unity.com/

driving through an African safari in a virtual pickup truck, experiencing different VR scenes. The scenes contained stimuli designed to elicit the emotions listed. Taking one VR scenes for example, the fear part (Figure 3.1 (C)) has a dinosaur attacking the pickup and yelling towards the user. The sad part has a wolf cub who has lost his mother and walking around his mother with a mourning sound. The disgusting part has a scene where there were rotten animal's bodies and blood littered along the road. The happiness part has butterflies flying around the pickup and beautiful flowers, green grass and trees were in the scene as well. The anxiety part has lions attacking another pickup and the driver crying for help. Each of the sections lasted for 45 seconds and the whole experience lasted for approximately four minutes. A transitional five-second black screen was shown between each segment of the experience.

3.2.1 The Design of the Experiences

The VR experiences were based on a jungle safari with various animals (including dinosaurs) moving through in the environment and supplemented with appropriate sound effects. The player was placed on the back of a virtual car, which moved on its own without any intervention from the player. In the real world, the player was standing with a hand-rest in front to maintain balance, if needed. The user was allowed to look around and rotate his/her head to experience the VR environment at will. However, s/he was not allowed to walk. We conducted pilot studies to make sure that the environments triggered the appropriate experiences associated with a specific emotion. For example, to trigger happiness we showed a waterfall and many butterflies flying around, while for fear, we presented roaring panthers and dinosaurs.

Most of the visual effects of interest were presented in front of the users' eyes within $200°$ horizontal field of view. However, there were sound effects that originated from behind the users.

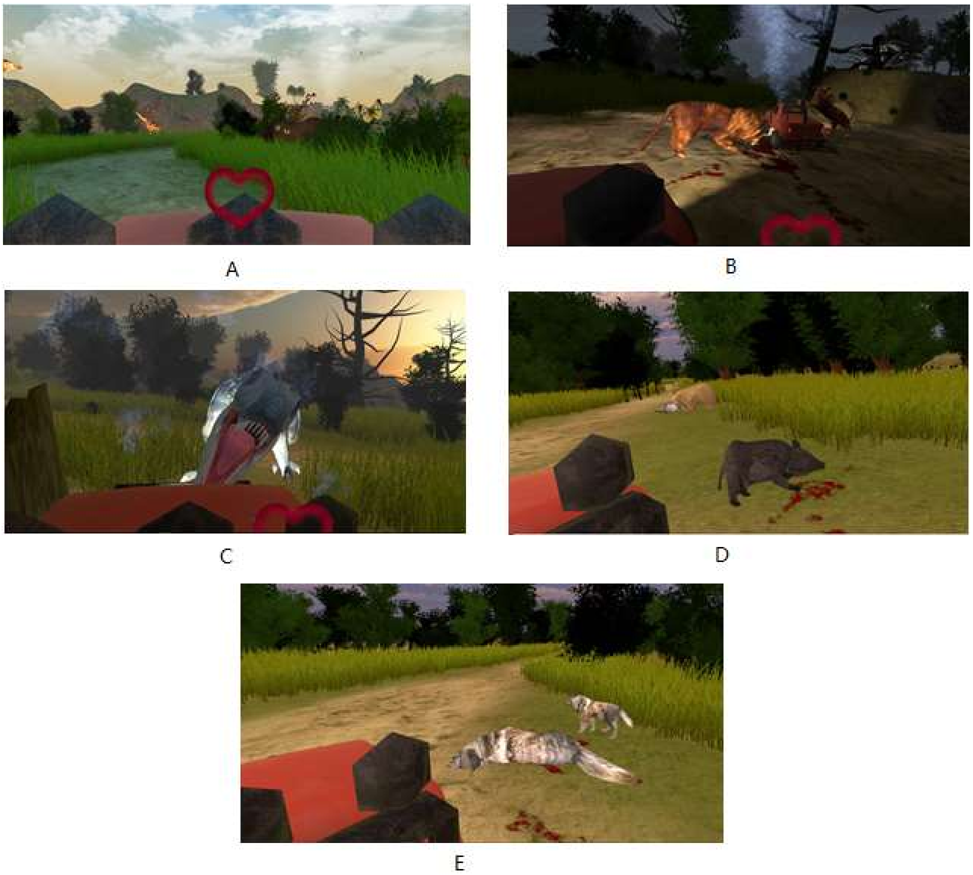


FIGURE 3.1: In each of the VR environments we designed five different emotional experiences of same length. The experiences were: happiness (A), anxiety (B), fear (C), disgust (D), and sadness (E). A full view of the visual HR feedback is shown in (A) [20]

3.2.2 Apparatus Used

The VR environment was experienced through an HTC Vive headset[2] and the sound was delivered through Logitech headphones (Figure 3.2). The Vive display was equipped with a Pupil Labs eye-tracker[3] to measure the pupil dilation of the user while experiencing the VR environments. The user was asked to stand and hold the Vive controllers in both of her hands and wore a Polar H7 HR sensor[4].

[2] https://www.vive.com/au/
[3] https://pupil-labs.com/pupil/
[4] https://www.polar.com/au-en/products/accessories/H10_heart_rate_sensor

FIGURE 3.2: Participants were wearing a HTC Vive display, Logitech Headphones, and Polar H7 HR sensor [20]

3.3 User Study

We designed and ran a within-subjects user study to evaluate the effects of different ways of displaying HR signal on the user's understanding of his/her own physiological state and the environment. In the following sub-section, we provide a detailed description of the user study design.

3.3.1 Independent Variable

The independent variable was Multi-Sensory HR Feedback with five different conditions; (1) None, (2) Audio-Visual, (3) Visio-Haptic, (4) Audio-Haptic, and (5) Audio-Visual-Haptic.

To convey HR information to the participant, we adopted a multi-sensory approach, particularly focusing on the audio, visual, and haptic senses. Visual feedback was given by displaying a red heart symbol on the screen, which changed its size proportionately to the change in HR. The auditory feedback was provided by the sound of a heartbeat played back through a Logitech noise-cancelling headphone. We adjusted the volume level of the headphone to the comfort level of the participants. The haptic feedback was provided as vibrations through the hand-held Vive controllers. The vibrations were synchronized with the participant's real-time HR. In one of the conditions (None), no feedback was provided. This served as a baseline or control condition for the experiment. In three conditions, we coupled two of the three senses, and in the fifth condition, we provided feedback via all senses together.

We counterbalanced the order of the feedback and environments using a 5x5 balanced Latin-square design, which enabled each environment to be experienced using different multi-sensory feedback an equal number of times.

3.3.2 Dependent Variable

We were mainly interested in the subjective preferences of HR feedback types. Hence, we primarily focus on qualitative data. We administered a Positive And Negative Affect Schedule (PANAS) scale [129], a Self-Assessment Manikin (SAM) questionnaire [13], and a subjective preference questionnaire that included the ranking of the multi-sensory feedback types (Table 3.1). In the end, we performed a short semi-structured interview with each of the participants. As quantitative variables, we measured the participants' real-time HR and pupil dilation during the experiences, and their head orientation during the task.

3.3.3 Experimental Task

The study task was simply to experience the immersive VR environments using the HTC Vive while leaning on a swivel chair and holding the controllers. We asked participants to stand throughout the experiment to reduce their physical movement, which could have confounded the experiment by increasing the HR. To maintain consistency among all conditions, we asked participants to hold the controllers even when haptic feedback was not given. First we explained the experiment to the participants, followed by signing of

TABLE 3.1: Five-point Likert scale questionnaire

Survey Questions	Scale	
	1	5
Q1 How much attention did you pay to your HR when in the game?	Very inattentive	Very attentive
Q2 How much did you feel your HR when in the game?	Very less	Very much
Q3 How much do you agree that you understood your HR accurately through the visualisation?	Very much Disagree	Very much agree
Q4 How much did the HR visualisation add to enhance the enjoyment when in the game?	Very less	Very Much
Q5 How much do you agree that the HR visualisation distracted your experience when in the game?	Very much disagree	Very much agree
Q6 Please rank the conditions according to your preference	Best	Worst

the consent forms and demographic data collection. We asked participants to relax for two minutes before starting the experiment. Then we collected baseline data for two minutes in a standing position without wearing any VR gear. Following the baseline data collection, we showed a peaceful demo VR environment to the participants for a minute, which enabled participants to get used to VR and possibly mitigate the effects of the novelty the device maybe have had for the first-time users. After that, participants were asked to relax for another minute before starting the main experiment.

Following the baseline HR data collection, participants started the first VR experience. Then the participants answered the questions. This process was repeated five times during the whole experiment. After all five experiences, we interviewed the participants. Participants were asked to take a break between each experience for as long as they wanted after completing the questionnaires. For each participant, the whole experiment took about 60 minutes on average.

3.3.4 Participants

We recruited a total of 20 participants (five female), with ages ranging between 22 to 58 years (M=31.65). Participants were recruited from the university students and staff and personal contacts of the authors. Nineteen participants had computer gaming experience and only nine participants had experience with VR. Fourteen participants reported that they normally did not pay attention to their HR in daily life. None of the participants reported any visual or auditory impairment.

3.3.5 Hypotheses

At the outset of the experiment, we had the following hypotheses.

- H1 The Audio-Visio-Haptic condition will be subjectively preferred significantly more and have the highest ranking of any condition, as this condition provides feedback through the highest number of modalities.
- H2 The Audio-Visio-Haptic condition will create significantly more positive effects than all other conditions
- H3 In general, conditions with visual feedback will receive lower preferences than conditions without visual feedback as the visual feedback may add distractions.
- H4 The baseline (None) condition will have significantly worse subjective preferences, as it does not provide any HR feedback.

3.4 Results

Overall we found that participants preferred to have HR feedback as all conditions with feedback were subjectively rated better than the None condition. The Haptic-Audio condition was found to be most preferred.

To analyse the data, we used the SPSS software, version v.21. To analyse the subjective data, we used non-parametric tests, and for objective data, we used repeated-measures ANOVA followed by a post-hoc test with Bonferroni's adjustments.

3.4.1 Ranking

We analysed the ranking data using a Friedman test and Wilcoxon signed-rank post-hoc tests. Overall, the **Audio-Haptic** condition was ranked the best and the baseline **None** condition was ranked the worst. A Friedman test showed an overall significant effect of conditions on ranking—$\chi^2(4) = 12.12$, p=0.016. A follow-up Wilcoxon signed-rank test revealed that the **Audio-Haptic** condition was significantly better than **None** (Z=-2.67, p=0.007), **Audio-Visual** (Z=-2.05, p=0.041), and **Visual- Haptic** (Z=-2.35, p=0.019). The **Audio-Visual-Haptic** showed a trend towards having a better rank (Z=-1.84, p=0.065) than the **None** condition. This ranking data (Table 3.2) clearly indicates that the participants preferred to have HR feedback during their gaming experience; in particular they preferred **Audio-Haptic** feedback.

3.4.2 Questionnaire

We asked participants to use a 5-point Likert-scale based questionnaire to report their feedback on several aspects. For each of the questions, we ran a one-way repeated measure ANOVA and a post hoc analysis with Bonferroni's adjustments. Overall, the baseline (None) was found to be less favourable to participants, although it caused the least distraction in the experience. Hence, the value of adding physiological feedback in VR experiences is established. Below we present the analysis in detail.

- Q1. How much attention did you pay to your HR when in the game? The analysis showed that participants paid significantly less attention to their HR in the baseline (None) condition than all other conditions F(4,76)=13.44, p<0.001, η_p^2=0.41, observed power=1.0. A post-hoc test showed that in the baseline (None) condition, participants were significantly less attentive to their HR than when they were in the VEs.

- Q2. How much did you feel your HR when in the game? We found, using ANOVA and post hoc tests, that participants felt their HR significantly less in the baseline (None) condition than all other conditions $F(4,76)=19.04$, $p<0.001$, $\eta_p^2=0.5$, observed power=1.0.
- Q3. How much do you agree that you understood your HR accurately through the visualisation? Similarly, the baseline (None) condition made participants significantly less understanding of their HR during the experiences than all other conditions $F(4,76)=18.77$, $p<0.001$, $\eta_p^2=0.5$, observed power=1.0.
- Q4. How much did the HR visualisation add to enhance enjoyment when in the game? Understandably, the baseline (None) condition added least to enhancing the enjoyment than all other conditions $F(4,76)=21.21$, $p<0.001$, $\eta_p^2=0.5$, observed power=1.0.
- Q5. How much do you agree that the HR visualisation distracted your experience when in the game? On a positive note, baseline (None) condition was significantly least distracting than all other conditions $F(4,76)=9.83$, $p<0.001$, $\eta_p^2=0.3$, observed power=1.0. However, this is understandable, as the baseline condition did not provide any additional feedback.

3.4.3 Positive and Negative Affect Schedule (PANAS)

The Positive And Negative Affect Schedule is a measure of overall positive and negative effects in a given experience measured through 20 different emotions and feelings [23]. Overall, there was more positive affect than negative affect in all conditions. However, we did not notice any significant effect of conditions on either positive affect $F(4,76)=1.79$, $p=0.14$, $\eta_p^2=0.1$; or negative affect $F(4,76)=1.07$, $p=0.38$, $\eta_p^2=0.05$ (Table 3.2).

TABLE 3.2: Mean and standard deviation values of ranking and questions

Conditions	Ranking	Q1	Q2	Q3	Q4	Q5
Baseline (None)	3.7 (1.7)	1.6 (1.0)	1.6 (0.9)	1.6 (1.0)	1.3 (0.6)	1.6 (1.3)
Audio-Visual	3.2 (0.9)	3.7 (0.9)	3.2 (1.1)	3.5 (1.1)	2.9 (1.0)	3.1 (1.3)
Visual-Haptic	3.4 (1.1)	3.5 (1.1)	3.2 (1.2)	3.2 (1.0)	3.1 (1.1)	3.1 (0.9)
Audio-Haptic	2.2 (1.3)	3.0 (1.2)	3.5 (1.1)	3.5 (0.9)	3.2 (1.1)	2.4 (1.0)
Audio-Visual-Haptic	2.6 (1.5)	3.6 (1.2)	3.8 (0.8)	3.7 (0.9)	3.1 (1.0)	2.9 (1.1)

TABLE 3.3: Mean and standard deviation values of PANAS and SAM Questionnaires

Conditions	Positive Affect	Negative Affect	Valance	Arousal	Dominance
Baseline (None)	28.2 (5.1)	19.5 (7.2)	2.9 (1.0)	2.8 (1.0)	2.6 (0.9)
Audio-Visual	27.9 (5.7)	20.8 (7.8)	2.7 (0.9)	2.8 (0.8)	2.5 (1.0)
Visual-Haptic	27.7 (6.2)	20.7 (6.5)	3.0 (0.8)	2.7 (0.8)	2.7 (0.9)
Audio-Haptic	27.0 (6.3)	19.1 (7.5)	2.9 (1.1)	3.1 (0.8)	2.5 (0.9)
Audio-Visual-Haptic	29.6 (5.2)	20.0 (6.6)	2.5 (1.1)	2.9 (1.1)	2.6 (0.9)

3.4.4 Semi-Structured/Informal Interview

After all the experimental sessions were completed, we asked participants about their opinions on the HR feedback methods and the VR environments. All the participants reported that they enjoyed the environments and felt different experiences within each environment, as we initially wanted them to. For example, P10 said "I thought it will be a pleasing safari as it started in the beginning but as the car took me through the jungle I started to feel different." P17 mentioned, "I felt sad for the poor wolf (Figure 3.1(E)) who just lost his mother." Except for one, all participants reported that the visual feedback was distracting and reduced the enjoyment of the safari to some extent. Out of 20, 17 participants reported that the audio feedback was most important for them and helped them the most to understand their HR. Among the remaining three participants, two participants preferred the haptic feedback and one preferred visual feedback. A couple of participants who reported the visual feedback to be distracting reported that they got used to the effect afterward and were able to focus on the VR environment more over time. In terms of ranking, most of the participants preferred the Audio-Haptic feedback among the five types of feedback.

In terms of the VR environment, participants wanted more interaction. For example, one participant (P4) wanted to be able to pet animals and another participant (P9) wanted to be able to touch trees. Among the scary effects, five participants reported that the human screaming was the most frightening effect.

3.4.5 Heart Rate

We measured the participants' HR while they were experiencing the game. We were particularly interested in investigating whether being in VR increased their HR from not being in VR and also whether there was any effect of the conditions on the average HR.

To analyse the effect of VR on HR, we compared the mean baseline HR with the mean of all VR session HR using a one-tailed paired t-test. We found that being in VR significantly increased the participants' HR: t(19)=-2.21, p=0.02. We also noticed a trend to significant increase HR when we compared the mean baseline HR with the mean HR of the first VR session for each participant: t(19)=1.54, p=0.07 (Figure 3.3). However, when we compared the mean in different conditions using a repeated measure ANOVA we did not notice any significant difference.

3.4.6 Head Movement

As an indication of how much participants looked around the VR environment in each condition, we measured their angular head movement in terms of both yaw (horizontal movement) and pitch (vertical movement). The data was collected as an angular distance between their head orientation at every second during the VR sessions.

We noticed that yaw was significantly affected by the conditions F(4,76)=4.41, p=0.003, η_p^2=0.18. A post-hoc test showed that the **Audio-Visual-Haptic** (M=3078.41, SD=1182.15) condition had significantly more yaw than the

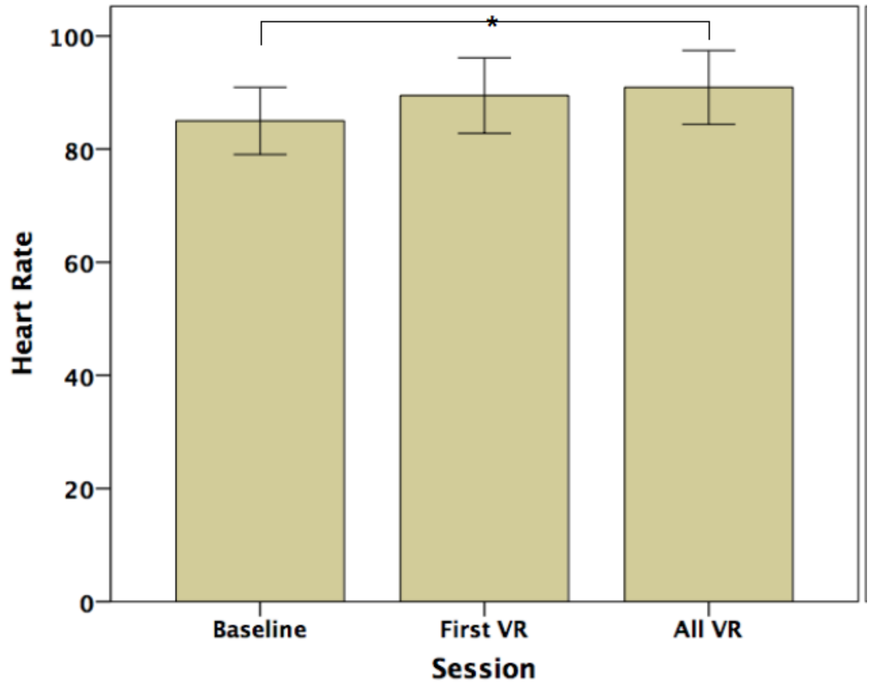


FIGURE 3.3: HR at baseline was significantly less than HR in VR sessions. Whiskers represent +- 95 % confidence intervals [20]

Audio-Haptic (M=2080.16, SD=698.23) condition (Figure 3.4). The reason for this effect is unclear. Probably, not having any visual HR feedback made participants see most of the environment without moving their head too much as the visual distraction was missing. However, we did not notice any significant difference between the conditions in the case of the pitch.

3.4.7 Pupil Dilation

We also measured the diameter of the pupil of the right eye during the task using Pupil Labs eye tracker. First, we measured dilation at baseline by systematically varying the brightness of the scene displayed through the HTC Vive display. Then during the experimental tasks, we measured the dilation. As different environments had a different average brightness, to analyse the data we normalized the dilation to 100 cd (candela) and measured the change in dilation as a ratio to the baseline data. However, we did not notice any significant difference between the conditions. Although, while being in VR (M=41.93, SD=9.7) the normalized pupil diameter increased slightly more

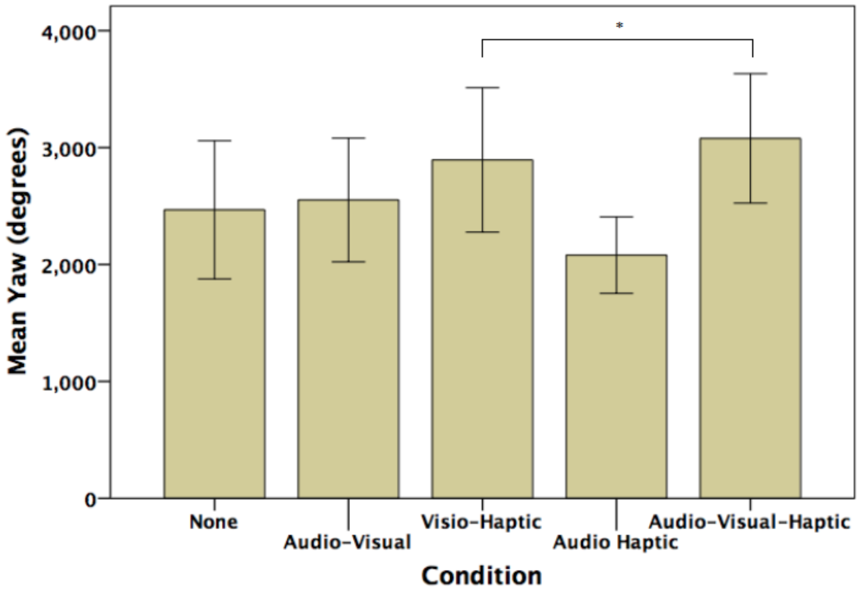


FIGURE 3.4: The yaw (horizontal head movement) was significantly more in the Audio-Visual-Haptic condition than in the Audio-Haptic condition. Whiskers represent +- 95 % confidence intervals [20]

than in the baseline (M=38.59, SD=13.1). However, the difference was not significant.

3.5 Discussion

In this work, we focused on single-user experience and provided HR feedback using combinations of visual, audio, and haptic modalities. We postulated four hypotheses at the beginning of the study. We expected the **Audio-Visual-Haptic** condition would create the highest positive affect and would be most preferred by the participants. This was because the **Audio-Visual-Haptic** condition provides feedback through the largest number of channels and it will help participants feel their HR the most. However, these two hypotheses were not supported in the user study. On the contrary, the **Audio-Haptic** feedback was most preferred and visual feedback was labelled as distracting by most participants. This makes sense as the visual feedback was a large red heart symbol changing its size based on the HR increase or decrease proportionally, which acted as a pre-emptive cue in the environment and attracted user attention most of the time, even when it was not desired. This was also a reason for the partial acceptance of Hypothesis 3, that we expected conditions with visual feedback would have less preference than conditions without visual feedback.

The final hypothesis that postulated that the **None** condition would have the worst preference was accepted as subjectively it was ranked and rated the worst. This is a clear indication that participants appreciated getting their own HR feedback and so future VR interfaces may consider including appropriate visualisation of physiological data in the experience.

We noticed that there was no significant difference in terms of PANAS and SAM scores in any of their subscales. We believe the VR experiences we used in the experiment were not long enough and we did not provide any interaction opportunities beyond just looking around. Also, if we increased the fidelity of the VR graphical elements the participants could have increased emotional arousal [122]. Overall, as far as the design space was concerned, through the initial exploration of the multi-sensory visualisations, we argue that audio feedback was the most suitable for providing HR feedback and seems to have the greatest effect on the users. First, this modality does not affect the visual experience of the VR environment and second, users are used to listening to heartbeat sounds, which enables them to comprehend the HR information more through audio feedback than any other feedback. One participant (P5) said, " ... it feels natural [to hear heartbeat]." Some participants also preferred haptic feedback over visual feedback. We believe haptic feedback is a more natural way of perceiving HR than visual feedback as in real life humans can feel their pulse through haptic feedback. Usually, there is no way for humans to see their heartbeat in natural environments, so we believe audio and haptic feedback are the most suitable and natural modalities for HR representation in a VR environment.

3.5.1 Limitations

In this chapter, we have performed a user study with customized experimental VR environments. However, the study has some limitations. First, we only considered an exploratory VR environment. There are several other environments that involve more active participation and interaction by the user, which we did not include in the study. Second, we have used only HR feedback in this study. However, there are other physiological measures that we could have used in the experiment but did not such as GSR and respiration rate. Thirdly, each emotional VR scene lasted only 45 seconds, and so there was no guarantee of evoking the expected emotion. Fourthly, we did not recruit the same number of female participants as the male in the user study. Fifthly, in our system, we designed one type of heart shape symbols as the HR feedback in VEs and the heart shape symbol is not 3D spatial. The design is not comprehensive and more HR visualisation designs are needed. Also, when we analysed HR data, we did not perform a time series analysis.

3.6 Conclusions

In this chapter, the goal was to explore the multi-sensory design space for providing feedback of physiological data to a user in an attempt to make them feel their physiological state. We presented four different multi-sensory visualisations of HR data in immersive VR experiences and compared these types of HR representations. It is important because knowing one's physiological state can help a person notice his emotion states and in a collaborative setup, it could help the collaborators share the physiological cues. Also, validating the feedback of physiological data in VR could help my later research.

We conducted a within-subjects user study with 20 participants and found that participants especially preferred the **Audio-Haptic** condition. Most of them reported the audio feedback to be most helpful.

Chapter 4

Manipulating Physiological Feedback in Immersive VR

In our second study, we explore how manipulating physiological feedback in an immersive virtual environment can influence a user's emotions in the VE. The study was presented as a full paper in the international and interdisciplinary conference (CHI PLAY2018) in Melbourne, Australia from 28th to 31st of October 2018.

4.1 Introduction

In the neuroscience research, it has been reported that manipulating HR variability can create different responses to anger-inducing stimuli [39]. A study reported that providing accurate HR biofeedback is an efficient way to control autonomic physiological reactions when people are exposed to negative stimuli [89]. There are also medical applications where VR has been used to treat a condition where emotion was used as a key measurement. Gomez et al. [45] reported using VR to facilitate Dialectical behavioural Therapy (DBT) and found that over time positive emotions increased and negative emotions decreased. A similar effect was noticed in work by Banos et al. [7], where elderly participants were found to have an increase in positive emotions and a decrease in negative emotions after being exposed to specially designed VEs. Researchers using VR-based interventions for Fibromyalgia [52] and autism spectrum disorder (ASD) [61, 55] measured emotions using subjective instruments. Ueoka et al. [119] conducted a study attempted to amplify the horror experience of watching 3D movies by providing pseudo HR, as did another study [118] using a horror VR experience, trying to amplifying the scariness of the experience further. They provided HR feedback through a vibrating floor.

In this chapter, we present work that systematically investigates the emotional and physiological effects of providing manipulated HR feedback to users in the single-user mode in VEs. Our study focuses on providing users with their own real-time HR feedback—in decreased, increased, and non-manipulated ways—via auditory and haptic channels. We measure if emotions can be altered and how real physiological signals could be affected by this modulation.

The main motivation of this work is to examine how additional physiological feedback, on top of traditional audio-visual effects in VR, can affect the overall experience, and whether or not some specific emotions can be enhanced or reduced by manipulating the feedback. This is important because VR applications are commonly used to treat various phobias [131, 78] and disorders [103]. If we can establish the effects of HR feedback manipulation found by others [89, 39] in VR applications as well, then treating conditions related to negative emotions using VR can become more effective than now. Similarly, in the case of entertainment and gaming VR applications, we could induce higher levels of emotion by manipulating HR feedback.

To investigate these effects, we designed five VEs of similar quality and experience. From the previous chapter, we know that participants prefer to receive HR-related feedback via the auditory-haptic channel. We implemented this finding in the current experiment as a means to study how the perceived HR variability influences emotion. For the user study, HR feedback was manipulated in five ways - decreasing by 15% and 30%, increasing by 15% and 30%, and a control condition in which no manipulation was performed on HR. In a within-subjects user study, participants relayed their experiences through two state-based emotion measuring subjective instruments. We also collected HR and GSR data during the experience.

4.2 User Evaluation

The main goal of the user evaluation was to investigate the emotional and physiological effects of providing manipulated (increased, decreased, and accurate) real-time HR feedback to users in an immersive VE.

FIGURE 4.1: Happiness [26]

FIGURE 4.2: Anxiety [26]

4.2.1 Experimental Virtual Environment

The VR experiences were based on a jungle safari with various animals (including dinosaurs) moving through in the environment and supplemented with appropriate sound effects (Figure 4.1, Figure 4.2, Figure 4.3, Figure 4.4, Figure 4.5). Each participant was a tourist on a virtual safari, placed in a standing position on the back of a virtual pickup truck moving along without

FIGURE 4.3: Fear [26]

FIGURE 4.4: Disgust [26]

any interaction from the player. We used this scenario for two reasons: (a) to provide participants with the greatest opportunity to explore the environment without worrying about controlling their movement, similar to most real-world jungle safaris, and (b) we wanted to control the path of the car for consistency in our experiment, as we placed different emotional triggers in the VE at particular locations. The elements that served as emotional triggers were carefully placed in a manner such that the participants could not avoid receiving them. Most of the visual effects of interest were presented in front of the participant's eyes within a $200°$ horizontal field of view. However, there were sound effects that originated behind the participant in the VE. We did not provide an avatar for the participants for self-awareness.

Using the Unity 3D game engine, we created five similar VEs for this experiment, each lasting for four minutes. In each of the environments, there

FIGURE 4.5: Sadness [26]

was a mixture of five different kinds of experiences—happy, anxious, scary, disgusting, and sad. We ran expert reviews and pilot studies to make sure that the emotional experience triggers were appropriate for their intended purposes. For example, to trigger happiness, we showed a waterfall and many butterflies flying around, while for fear, we displayed roaring panthers, dinosaurs, and snakes attacking the car. In the case of sadness, a deer accidentally hit the pickup and died. However, in our measurements, we took a holistic approach and did not distinguish between the experiences as it is difficult to ensure that participants would feel only one emotion at any point in time.

In the real world, the subject stood with a hand-rest in front to maintain balance, if needed. The subject was allowed to look around and rotate his/her head to experience the VE at will. However, s/he was not allowed to walk as we wanted to avoid any elevated physiological signals due to locomotion.

4.2.2 Experimental System and Setup

The scenes were experienced by the participants through an HTC Vive HMD and the audio effects were provided through Logitech noise-cancelling headphones. We also provided HR feedback to the participants while in the virtual experience via a combination of auditory and haptic feedback [20]. While the sounds of HR were provided through the headphones, the haptic feedback

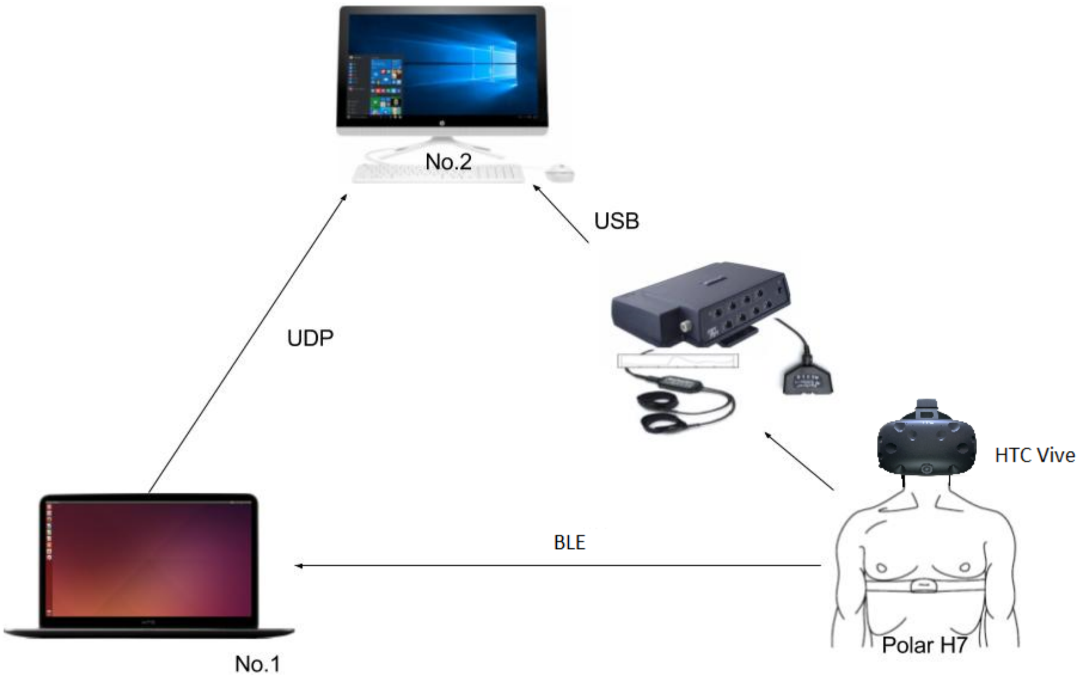


FIGURE 4.6: The system overview [26].

was provided through both of the Vive controllers, which participants were holding in their hands.

To capture the physiological signals including HR and GSR, we used the ProComp Infiniti 8 Channel Encoder by Thought Technology[1]. The HR sensor we used was a Polar H7. Through the EKG receiver, the signal from Polar H7 could be processed through a Procomp Infiniti Encoder.

The GSR sensors were attached to two fingers of the participants, and the Polar H7 was strapped around the chest. In order to stream HR in real time, we used the Generic Attribute (GATT) profile[2] to get HR data from Polar H7 via BLE. Figure 4.6 shows the system we designed for our user study. In the figure, the laptop labelled as No. 1, running Ubuntu, received HR data directly from the Polar H7 via Bluetooth. The data was then streamed to computer No. 2 in real time, where HR data was visualised in Unity using audio and haptic cues. At the same time, the GSR and HR data were recorded in the No. 2 computer using BioGraph Infiniti software of Thought Technology.The user was asked to stand and hold the HTC Vive controllers in both of his or her

[1]http//thoughttechnology.com/index.php/
[2]https://www.bluetooth.com/specifications/gatt/

hands.

4.2.3 Independent Variable

We ran a very focused within-subjects study. The only independent variable in this experiment was *HR* feedback manipulation. We experimented with five different levels of the manipulation— **-30%, -15%, Real (0%), +15%, and +30%**. In the -30% and -15% conditions, the real-time HR feedback was provided after reducing HR by 30% and 15%, respectively. Similarly, for +30% and +15% conditions, the HR feedback was 30% and 15% higher than the user's real HR. In the Real condition, the HR feedback was provided without any manipulation. These levels of manipulations were chosen after a short pilot study with five participants where we varied the range between $\pm 50\%$ with 10% intervals. We noticed beyond $\pm 30\%$ the manipulation becomes too obvious to the participants.

In the study, each participant experienced the above five levels using five different VE scenes to avoid any learning effects. The order of the presentation of the manipulated feedback was counterbalanced using a balanced Latin square approach.

4.2.4 Dependent Variables

Our main aim was to identify the effect of HR feedback manipulation on emotions. As such, we used two validated subjective emotion-measuring surveys, the PANAS [129] and the SAM questionnaire [13]. Additionally, a semi-formal interview was conducted with participants at the end of the study.

The PANAS scale was used as it provides an overall state-based positive and negative affect score, measured through the scores for 20 individual feelings and emotions. SAM provides scores for overall arousal, valence, and dominance. Besides the subjective measurements, we also collected HR and GSR data during the virtual experience sessions.

4.2.5 The Experimental Procedure

After welcoming the participant, we explained the task and asked them to fill out a consent form and demographic questionnaires. We clearly informed the participant that the HR feedback they would be getting would be their own real-time HR data. However, we did not disclose that their HR feedback would be manipulated. After attaching the sensors to the body, we asked them to wait for three minutes to bring their HR to a normal level, following which we collected baseline HR and GSR data for two minutes. During this time, we asked the participant to stand as the experimental task also required them to stand. After collecting the baseline data, the participant waited, sitting for at least two minutes, before starting their first experimental session.

On completing the first session where participants wore the HMD and viewed the safari in a car, they answered the PANAS and SAM questionnaires and waited another minute before starting the next session. This process was repeated five times. After all the experimental sessions were completed, we interviewed the participants. Following this, participants were informed about the motive of the study and the procedures that were followed to convey HR data to them. On average the experiment took about an hour per participant.

4.2.6 Participants

We recruited 20 participants from university students and staff and from personal contacts. One participant had to drop out after two sessions due to a personal emergency, which resulted in the study being finalized with 19 participants (two female) with ages ranging between 21 and 45 years (m=30.6, sd=7.1).

Eighteen of the participants had prior experience playing video games, and 13 participants reported that they had experience with VR. Only two participants reported that they paid attention to their HR in daily life. Eighteen participants thought their HR increased when they felt stressed, afraid, or anxious, and 16 participants thought their HR decreased when they felt relaxed, bored, or sleepy.

We used G*Power [31] to calculate the sample size for repeated measure ANOVAs with a large effect size of ($f = 0.4$) and $\alpha = 0.05$, and found we required 13 participants for our study, meaning we had more than the required number to get enough power for our statistical tests.

4.2.7 Hypotheses

At the outset, we had the following hypotheses:

- H1: **-30%** and **-15%** feedback will cause less interest in the virtual experience than **real, +15%, and +30%** feedback.
- H2: **+30%** and **+15%** feedback will cause more excitement in the virtual experience than **real, -15%, and -30%** feedback.
- H3: **+30%** and **+15%** HR feedback will cause more anxiety, fear, and nervousness than **real, -15%, and -30%** feedback.
- H4: There will be a significant difference in HR and GSR between the different conditions.

4.3 Results

To analyse the non-parametric subjective data, we used Friedman's ANOVA. For the objective data (HR and GSR), we used repeated measure ANOVAs. Table 4.1 gives an overview of responses from the PANAS and SAM questionnaires. Overall, we found that slightly elevated HR feedback (**+15%**) over **real** caused more excitement, scariness, nervousness, and fear. A slightly lower HR (**-15%**) resulted in participants being more interested in the VE. However, the effects were mainly noticed in the subjective responses, and the physiological responses remained largely unaffected by the different HR feedback.

TABLE 4.1: The Mean and standard deviation values of PANAS and SAM questionnaires.

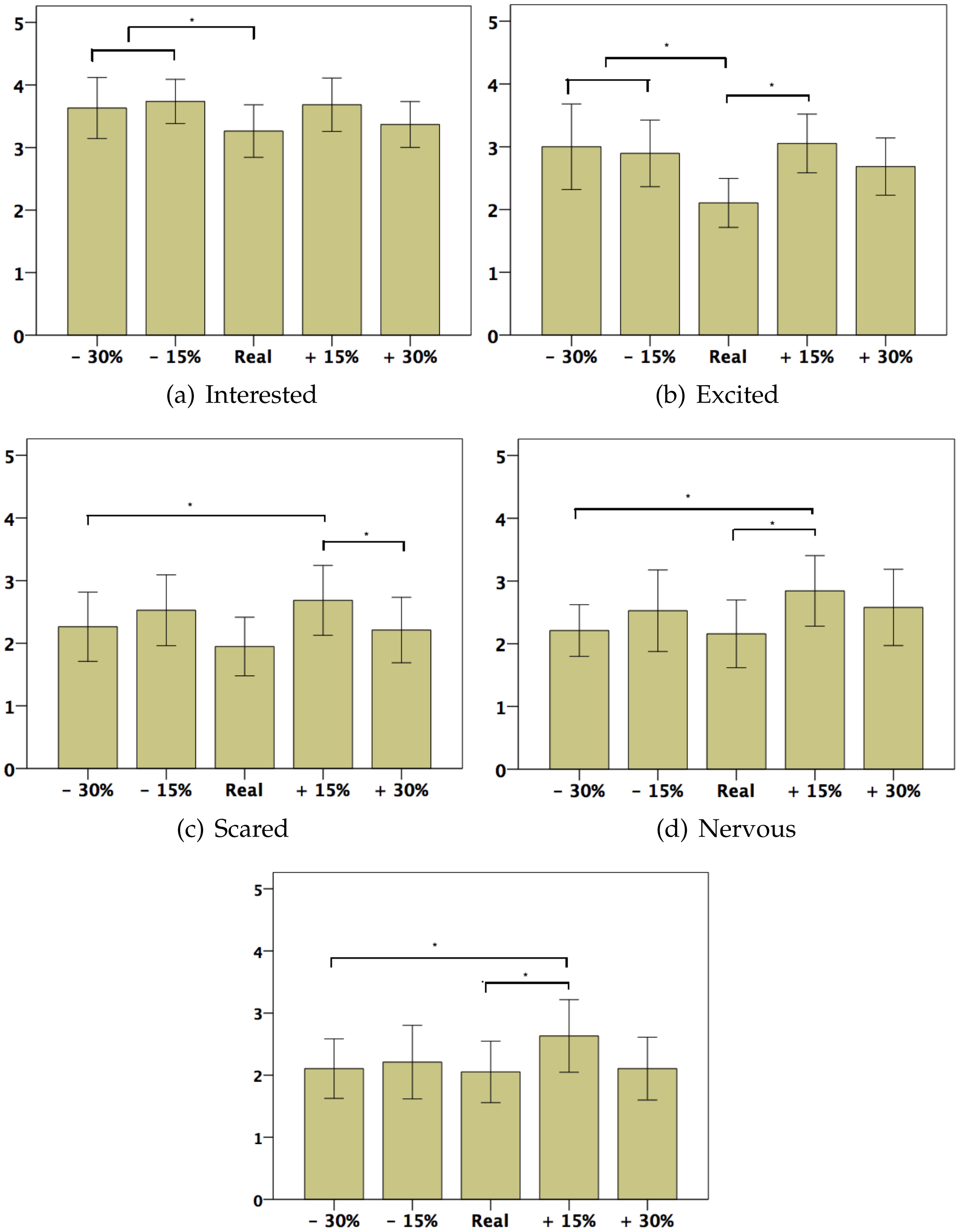
Heart Rate Manipulation	PANAS							SAM		
	Positive Affect	Negative Affect	Interested	Excited	Scared	Nervous	Afraid	Valance	Arousal	Dominance
- 30%	25.4 (8.4)	20.5 (7.6)	3.6 (1.0)	3.0 (1.4)	2.3 (1.1)	2.2 (0.9)	2.1 (1.0)	2.8 (0.9)	2.9 (1.1)	2.9 (1.0)
- 15%	26.3 (7.2)	22.3 (9.4)	3.7 (0.7)	2.9 (1.1)	2.5 (1.2)	2.5 (1.3)	2.2 (1.2)	3.2 (1.1)	2.7 (0.9)	2.8 (1.1)
Real	23.1 (6.3)	19.6 (7.8)	3.3 (0.9)	2.1 (0.8)	1.9 (1.0)	2.2 (1.1)	2.1 (1.0)	3.2 (0.8)	2.8 (0.8)	2.8 (0.9)
+ 15%	26.0 (6.6)	22.6 (8.3)	3.7 (0.9)	3.1 (1.0)	2.7 (1.2)	2.8 (1.2)	2.6 (1.2)	3.1 (0.9)	2.9 (1.0)	3.1 (1.0)
+ 30%	24.9 (6.9)	22.4 (9.6)	3.4 (0.8)	2.7 (0.9)	2.2 (1.1)	2.6 (1.3)	2.1 (1.0)	3.3 (1.1)	2.7 (1.3)	3.2 (0.9)

4.3.1 Analysis of PANAS and Individual Emotions

We noticed that in all conditions, positive affect was stronger than negative affect. However, there was no significant difference between the conditions on either positive affect (p=0.17) or negative affect (p=0.18). We noticed among the 20 different emotions and feelings measured using PANAS, five individual emotions were significantly influenced by the HR feedback manipulation—interest, excitement, scariness, nervousness, and fear. Interestingly, these five emotions are clearly most relevant for the VEs we designed.

Interest: With a Friedman test, we found a significant effect of HR feedback manipulation on participant interest while being in the VE—$\chi^2(4) = 10.5$, p=0.03. Using a post-hoc Wilcoxon signed rank test we found that **real** HR feedback was significantly less interesting than **-30%** (Z=-2.1, p=0.03) and **-15%** (Z=-2.5, p=0.01) feedback. It was also almost significantly less than **+15%** (Z=-1.7, p=0.08). We also found a strong trend for **+30%** being less interesting than **-15%** feedback (p=0.06), which participants reported to be the condition that made them the most interested while experiencing the VE (Figure 4.7(a)).

Excitement: We found a significant effect of HR feedback manipulation on the feeling of excitement while in the VE—$\chi^2(4) = 15$, p=0.005. With a post-hoc test we found that, similar to interest, **real** feedback made participants feel significantly less excited than **-30%** (Z=-2.1, p=0.03), **-15%** (Z=-2.6, p=0.008), and **+15%** (Z=-2.5, p=0.01) feedback. We found that **+30%** feedback made participants almost significantly less excitement than **+15%** feedback, which was the feedback that made participants most excited while in the VE (Figure 4.7(b)).



(a) Interested

(b) Excited

(c) Scared

(d) Nervous

(e) Afraid

FIGURE 4.7: In the PANAS questionnaire, we noticed significant effects of HR feedback manipulation in feelings of being (a) interested, (b) excited, (c) scared, (d) nervous, and (e) afraid. The whiskers represent ±95% confidence interval [26].

TABLE 4.2: The mean and standard deviation values of the physiological data.

Heart Rate	Heart Rate			Galvanic Skin Response	
Manipulation	Raw	Difference	Variability	Raw	Difference
Baseline	87.3 (11.9)	---	36.3 (60.6)	1.8 (1.2)	---
- 30%	89.3 (13.4)	2.0 (5.8)	21.4 (12.3)	6.7 (6.8)	4.9 (6.0)
- 15%	88.5 (12.2)	1.2 (6.7)	20.9 (10.7)	5.9 (6.1)	4.1 (5.3)
Real	87.6 (13.1)	0.3 (6.2)	22.4 (12.7)	5.6 (4.4)	3.8 (3.5)
+ 15%	88.7 (13.7)	1.4 (6.7)	21.0 (12.6)	6.3 (5.0)	4.5 (4.3)
+ 30%	88.7 (13.2)	1.5 (5.4)	21.6 (11.1)	6.9 (5.9)	5.1 (5.2)

Scariness: There was a significant effect of HR feedback manipulation on evoking scariness in VE—$\chi^2(4) = 12.9$, p=0.012 (Figure 4.7(c)). A post-hoc test revealed that **+15%** feedback was able to create significantly more scariness in participants than **+30%** (Z=-2.48, p=0.013) and **-30%** (Z=-2.53, p=0.01) feedback. There was a trend for **Real** feedback making participants feel less scary than **+15%** feedback (Z=-1.8, p=0.07). **Real** evoked significantly less scariness than **-15%** feedback (Z=-2.3, p=0.02).

Nervousness: We noticed that HR feedback manipulation had a significant effect on the feeling of nervousness—$\chi^2(4) = 10.6$, p=0.03. A post-hoc test showed that **+15%** feedback, which caused most nervousness (Figure 4.7(d)), made participants significantly more nervous than **Real** (Z=-2.38, p=0.018) and **-30%** (Z=-2.3, p=0.02) feedback. **Real** feedback also made participants less nervous than **-15%** (Z=-2.8, p=0.005) feedback and there was a trend for it making them less nervous than **+30%** (Z=1.7, p=0.09) feedback.

Fear: We found a significant effect for HR feedback manipulation on feeling afraid—$\chi^2(4) = 10$, p=0.04 (Figure 4.7(e)). A Wilcoxon signed rank post-hoc test found that **+15%** caused significantly more fear than **Real** (Z=-1.9, p<.05) and **-30%** (Z=-2.5, p=0.01). Interestingly, there was a trend for **+30%** causing less fear than **+15%** feedback (Z=-1.8, p=0.07).

4.3.2 Interviews

After all the sessions were completed, participants were interviewed in an informal way. They reported that the VEs were indeed interesting and made them feel different in different segments. For example, P5 mentioned that "...the night scene where dinosaurs attacked the car was very scary." and p6 said that "...the scream from a woman who was attacked by a lion was scary and made me want to take off the headphone". However, P12 reported that he/she would have more feeling while in the VEs if the graphical fidelity was higher. This participant reported a lot of experience playing VR games using the HTC Vive.

The most interesting insights came when we asked participants about whether or not they felt their HR was accurately represented in the sessions. P15 made an interesting comment that "...if I was in control of the car then I might have felt a higher level of emotions." All participants, except for two, thought their HR was a bit faster than what he/she was expecting in one condition (**+30%**), otherwise, the HR was accurate. The other two participants thought that their HR was shown accurately in all conditions. Two participants explicitly reported that they thought their real HR went up in the **+30%** condition. In other words, from the interview it was clear that elevating HR feedback to **+30%** was noticeable, but other conditions (including **-30%**) went unnoticed.

Participants reported that they paid attention to the HR feedback more when at the beginning of the experiences and when nothing much was happening in the VE (e.g., in the happy segments). As the experiences progressed and more things started happening, the feedback became part of the experience and they did not notice it anymore.

4.3.3 Analysis of Physiological Data

Besides the qualitative responses, we were also interested in investigating whether HR feedback manipulation could affect the real physical HR and GSR of participants.

Heart Rate: In the case of HR, we analysed the raw data, the change from the baseline, and the variability. For HR variability, we measured the root mean square of the successive differences (RMSSD). However, we did not notice any significant difference in any of the HR measures.

Galvanic Skin Response: We measured the raw GSR and difference in GSR between baseline and other HR feedback manipulation conditions. In the case of GSR, we noticed a significant difference between baseline and all other VR exposure conditions—F(2.12, 37.9)=8.82, p=0.001, η_p^2=0.33, observed power=0.97 (Table 4.2). As the data did not meet the assumption of Sphericity we used the Greenhouse-Geisser adjustments. The GSR in the baseline was significantly lower than all other conditions. However, we did not notice any difference between the HR feedback manipulation conditions.

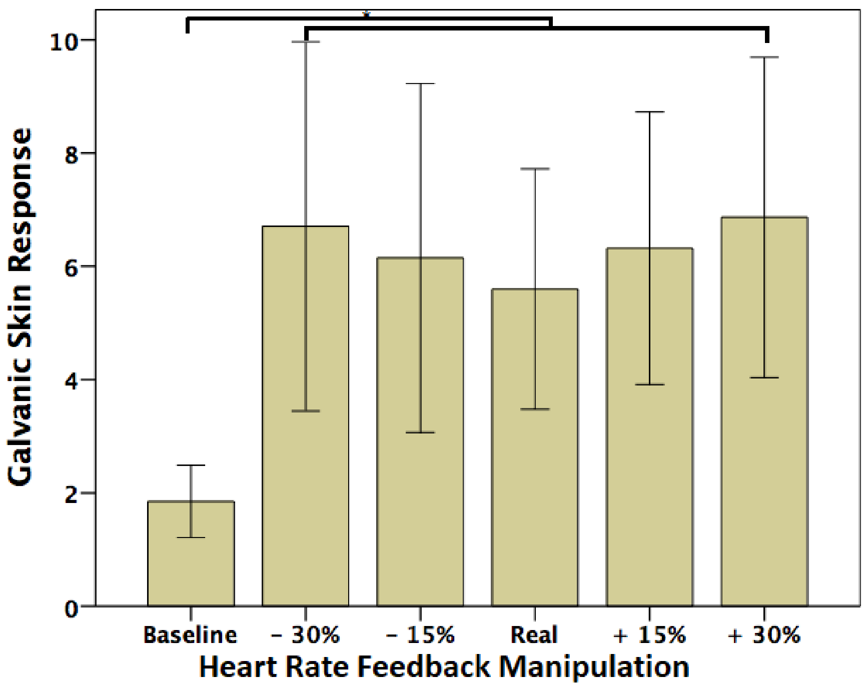


FIGURE 4.8: The mean GSR data shows a significant increase in arousal in the VR conditions compared to Baseline. The whiskers represent the $\pm 95\%$ confidence interval [26].

4.4 Discussion

In this experiment, we found that manipulating the HR feedback had a significant effect on emotions, but not on physiological signals. As expected, we noticed that positive affect was significantly stronger than negative affect in our VEs. However, there was no difference between the conditions, though the **Real** (not manipulated) HR feedback had the lowest positive affect and the lowest negative affect.

Besides overall positive and negative affect, we were also interested in five key emotions that were relevant for our VEs—interest, excitement, scariness, nervousness, and fear. Interestingly, in all five emotions, there were significant effects of HR feedback manipulation.

In our first hypothesis (H1), we expected that providing feedback that represented a slower HR than what it was in reality (**-30%** and **-15%** feedback) would decrease interest in the VE in comparison with all other feedback. Contrary to our expectations, we found that **-15%** HR feedback made participants significantly more interested in the VE, and **Real** HR feedback made participants the least interested. A possible reason for this effect is that finding one's HR to be slower than what it actually was made a participant feel more in control and provided courage to explore more, hence increasing interest. Although our hypothesis was not accepted, this is an interesting finding as future VR applications can provide real-time HR feedback that indicates lower HR to participants in order to make them more interested while in the experience.

Our second hypothesis (H2) predicted that faster HR feedback (**+30%** and **+15%**) would increase excitement while being in the VE than all other conditions. This hypothesis was partially accepted, as we found that **+15%** feedback made participants most excited of all feedback. However, the difference was only significant compared to the **Real** feedback. Interestingly, **Real** HR feedback made participants significantly less excited that in the other conditions, except for **+30%**. When the feedback was increased to the **+30%** level, participants became less excited. This means that faster-than-real HR feedback can increase excitement. However, when it goes beyond a threshold (in our case +15%) the effect reverses. We believe that when HR gets too fast, it can become apparent to the participant that they are being manipulated, and the excitement can fade away. In our interviews with participants, we found that almost all participants noticed when their HR feedback was provided at the +30% level, but they did not notice anything unusual when it was at the -30% level. We think that people expect their HR to be lower, and do not pay attention when they find it that way. Another explanation of this effect could be, that with a faster HR, the sound frequency of the beats and vibration of the controllers also increases, which may have made participants disengage with the experience.

Our third hypothesis (H3) predicted that scariness, nervousness, and fear would increase when faster HR feedback is provided in comparison to real and slower HR feedback. For all three emotions, we found that **+15%** HR feedback caused the highest effects, although the effect was not always significant, which indicates that our hypothesis was partially accepted. **Real** and **-30%** feedback had the smallest effects in making participants feel scared, nervous, or afraid. This effect is expected, as is often the case in movies and other audio-visual media, a faster HR feedback is associated with negative emotions. This result is consistent with the findings of Perira et al. [89], where they found that accurate (**real**) HR feedback can help control negative emotions. It also establishes that manipulating and providing physiological feedback in VR is consistent with the effects found in the physical world, which is very encouraging for future VR applications, particularly those that deal with negative emotions. However, the fact that **+30%** had similar effects as **real** feedback shows that audio-haptic feedback should not cross a certain upper threshold to keep the users engaged in the experience.

Our final hypothesis (H4) predicted that there would be a significant difference in physiological signals between the HR feedback manipulation levels. However, we did not find any support for this hypothesis, as there was no noticeable difference in either HR or GSR measures. However, we noticed higher arousal while being in VR than in the baseline condition. Although, this hypothesis was not accepted, this is an encouraging finding, as significantly altering physiological signals may cause detrimental effects for various medical reasons. The fact that by manipulating HR feedback we can alter emotions, but not physiological signals, makes this type of feedback safe for future VR applications.

Overall, our results indicate increasing negative emotions such as scariness, nervousness, and fear, **+15%** feedback should be used. **Real** feedback creates the least effects on any of these emotions, whereas **+30%** feedback causes detrimental effects and should be avoided. In VR, emotions can be altered without altering physiological signals, which are controlled by the autonomic nervous system.

4.5 Conclusions

In this chapter, we have presented a study in VR where the effect of manipulating multi-sensory HR feedback on user emotions was investigated. We found that interest, excitement, scariness, nervousness, and fear can be enhanced by providing manipulated HR feedback, although physiological signals remain unaffected. This is an interesting finding for VR researchers and virtual experience designers, as by using these r n in a more controlled way than previously, by simply providing and manipulating HR feedback. We believe our work could have an impact in creating more empathic and emotionally aware VR applications in the future.

4.5.1 VR Experience Design Guidelines

We have received several valuable insights from this study, which could be useful for future VR application design. We would like to follow these guidelines in our future research.

- **Provide** $\pm 15\%$ **HR feedback:** We noticed that manipulating HR feedback can increase interest, excitement, scariness, nervousness, and fear. The effects were most noticeable when either +15% or -15% HR feedback was provided. We would recommend providing slightly increased or decreased HR feedback when the application requires an increase in emotions, for example in VR games and movies.

- **Provide real HR feedback:** We also noticed that **real** HR feedback caused the least amount of emotion among the manipulation levels with which we experimented, which is supported by other research in neuroscience, and that real HR feedback can help control negative emotions [89]. Therefore, we would recommend providing real HR feedback in VR applications where controlling emotions is required.

- **Let the user drive and/or interact:** Participants in our study expressed a desire to be in control of the virtual car or having opportunities to interact with the virtual animals such as patting or pushing them, but we did not add these interactions for the sake of controlling the experimental conditions. However, in non-experimental experiences, we would recommend adding more interaction than just looking around.

4.5.2 Limitations and Future Work

Although we are reporting on our first study investigating these effects and found some interesting results, our experiment had some limitations. First, the experimental environments were mostly exploratory, with little interaction. We designed them that way to reduce any confounding effects of excessive physical movement on increased HR. Second, we did not measure the effects of manipulated HR feedback on Presence in the VE as we wanted to keep the overall task load reasonable for the participants. However, we understand the need for higher Presence and would like to investigate this effect in a future study. Third, we used only five discrete manipulation factors of $\pm 30\%$, $\pm 15\%$, and 0%. While we could identify the effects based on these manipulation factors, they do not confirm whether or not these are the thresholds where the emotional manipulation is the highest; there may be other manipulation factors where we can get better effects. It would be interesting to identify what exact levels of manipulation are most effective for each of the key emotions. Fourth, some of our results relied upon the participants' perception of their own HR, for example subjective question 3. However, HR is a physiological measurement, so the participants may have an inaccurate perception about their own HR. Although, this limitation is not easy to overcome.

In the future, we would like to explore sharing physiological cues in VR environments between two users instead of sharing the user's own physiological signal as a biofeedback, and see how the sharing of physiological cues could affect the other's emotions. We would also like to design different types of collaborative virtual environments, such as VR shooter games, or puzzle-solving activities, and see if HR feedback manipulation is effective in these settings.

Chapter 5

The Effect of Sharing Real-Time Multi-Sensory HR Feedback in Different Immersive Collaborative Virtual Environments

In Chapter 3 and Chapter 4, we reported on how physiological signals affected the users' emotions in subjective and objective ways in a single-user mode, where one user experienced different VR environments and only heard or felt his/her own heartbeat in the VR scenes. In this chapter, we will investigate the effect of sharing heartbeats between two users in the same virtual environment. The heartbeat of each user will be conveyed to the other person via audio and haptic modalities. This study was presented as a full paper in ISMAR 2018 conference, which was held in Munich, Germany from 16th October to 20th October 2018.

5.1 Introduction

In the previous search of emotion in VR, most of this research describes single-user applications, such as [20, 36, 26] and my researches in Chapter 3 and Chapter 4. Collaborative applications are the ones that can further realise Thomas' vision, namely "In the future, it might be possible for VR to give one person the feeling of being someone else" [115], and make collaborators more empathic to each other. However, there has been less research on how VR can be used to share the feelings or emotional state of one person to another in real time.

In this chapter, we have designed three different collaborative environments that represent different types of real-world collaboration and require different kinds of interactions (more details are given in Section 5.2). We explore how sharing HR feedback, in real time with each collaborator in a collaborative environment can affect Social Presence, emotional affect, and real HR signals. This research will provide an insight into the types of VR experiences that will yield different emotional responses and how these environments can be designed to make collaborators more empathic to each other. We empirically evaluated the effects in a user study with 18 participants. Participants reported that different environments had different effects on Social Presence and receiving HR feedback helped them better feel the presence and emotional state of the other collaborator.

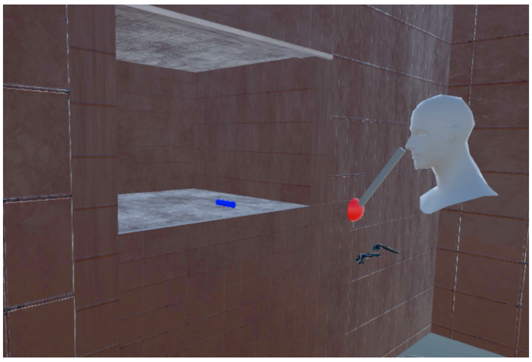
5.2 User Experiment

Following the outcomes of our earlier studies [20, 29], and feedback received from participants, we designed a follow-on study to evaluate the effects of providing multi-sensory (audio-haptic) HR feedback between each of the collaborators in three different types of collaboration tasks in VR. We were mainly interested in measuring the emotional effects and Social Presence. We designed the study to be *mixed-factorial* with one within-subjects and one between-subjects variable.

5.2.1 Independent Variables

1. HR Feedback (ON, OFF) — *between-subjects*

In a *between-subjects* variable, we provided real-time HR feedback to the participants using the audio-haptic multi-sensory channel. Participants were



(a) Escape Room

(b) Exploration

(c) Furniture Arrangement

FIGURE 5.1: We designed three different collaborative virtual environments. All participants experienced all environments as a within-subjects variable [28]

categorically told that the HR feedback they were receiving was of their partner and that he or she was also receiving the same feedback from them, and that the HR feedback was in real-time. In the ON group, the participants received the feedback through Logitech headphones with a beating sound (audio) and vibration through the handheld HTC Vive controllers (haptic). The volume was adjusted so that the participants could hear each other talking while collaborating. The OFF group did not receive the feedback, but they were also asked to wear headphones and hold controllers to maintain consistency between the two conditions.

2. Collaboration Environments (Exploration, Furniture Arrangement, Escape Room) — *within-subjects*

Using the Unity 3D game engine, we designed three different collaborative virtual environments, used as a *within-subjects* variable (Figure 6.2). The three different environments each had a different type of collaboration. In all of these collaborations, one collaborator was the experimenter (the author) and the other collaborator was the participant. This design was adopted to reduce any variation in communication style, physiological differences, and experience with VR technologies. In all the environments, participants saw each other as a generic unisex head model (as shown in Figure 6.2) tracked with the movement of the physical head of the participant and the controllers at their hand locations. We *counterbalanced* the presentation of these environments between participants using a Latin Square. All environments were carefully designed to be experienced by participants for approximately four minutes each. In the rest of this section we describe these environments in more detail.

Environment 1: Escape Room: This game was designed with inspiration from real-world escape room games. Collaborators had to find a few objects hidden in the room and put them into a collection box. They had four minutes to find all the objects and place them in order. This environment required both of the collaborators to work together and they each had equal roles in the task. Also, this task required a lot of interaction with the environment including opening drawers, pulling handles, holding objects, etc. The movement in the scene was controlled by the HTC Vive controllers' touchpad. This environment simulated real-world co-worker relationships (Figure 5.1(a)).

Environment 2: Exploration: In this VR application, the collaborators were automatically moved through an environment that had a mixture of scenes triggering a mix of emotional feelings such as fear, happiness, sadness, disgust, and neutral. For example, to trigger fear we placed participants on a dark path in a jungle with different sound effects. To trigger happiness we showed a bright city skyline with smiling people and butterflies. Disgust was triggered by placing participants in an area full of garbage bins and dead animal bodies, etc. Participants could turn their heads to explore the environment but no other interaction was available. Most of the visual effects of interest were presented in front of the users' eyes within a 200° horizontal field of view. However, there were sound effects that originated behind the users. This simulated a journey through the environment without needing to interact with it e.g., travelling in a vehicle of some type (Figure 5.1(b)).

Environment 3: Furniture Arrangement: In this environment, collaborators had to place six different pieces of furniture in a room. There were nine different options available shown as images on one wall and collaborators had to discuss and select the furniture one by one and place it in the room. The experimenter was the collaborator working and discussing with the participant which furniture to pick and where it should be placed in the virtual room. The participant manipulated the objects in the whole game. The movement was controlled using the touchpad of the controllers and pieces of furniture were selected using the trigger button of the controllers. For example, if one of the participants pointed at a picture of a piece of furniture and pressed the trigger button, a virtual model of the furniture then dropped on the ground, which was then placed at a location instructed by the experimenter in VR (Figure 5.1(c)). Once the furniture appeared in the room it could be further manipulated and placed as desired. This environment simulated a teacher-student or instructor-trainee relationship in the real world.

5.2.2 Dependent Variables

We were mainly interested in Social Presence and emotional effects, so we used several validated subjective questionnaires in addition to our own questions—the Social Presence Questionnaire (SPQ) [47], PANAS [129], SAM [13], and the Inclusion of Other in the Self Scale (IOS) [3].

We used four sub-scales of the Social Presence questionnaire—Co-presence, Attention Allocation, Perceived Message Understanding, and Perceived Behavioural Independence.

The PANAS scale measures 20 different feelings and emotions grouped in the equal number of positive affects (PA)—e.g., interest, attention, excitement, etc.—and negative affects (NA)—e.g., distress, scariness, nervousness, etc. Besides measuring just positive and negative affects, we have also measured a derived variable—PA/NA Ratio—where a higher value indicates more positive affect per unit negative affect.

FIGURE 5.2: Experimental setup [28]

We asked four additional questions of participants after each task where they had to rate their answers between 1 and 7. The questions were:

1. How strongly did you feel the other person's presence during the task? (1 = Not at all, 7 = Very Strongly)
2. How much did you feel the other person's emotional state during the task? (1 = Not at all, 7 = Very Much)
3. How confused did you get with the HR feedback? (1 = Not at all, 7 = Very Confused)
4. How much do you think your collaborator helped you in the task? (1 = Not at all, 7 = Very Much)

Objectively, we measured two types of physiological data—HR and respiration rate—using the Zephyr Bioharness3 sensor.

5.2.3 Experimental Setup and Procedure

The experiment was conducted in a 3.3x3.5 m^2 room. We used two HTC Vive HMD displays each connected to a desktop PC with Intel Core i7 3.4GHz, 16 GB RAM, and Nvidia Geforce GTX 1080 graphic card. For sound, we used the Logitech G933 headphones with Dolby 7.1 surround sound support. The physiological data were collected using the Zephyr sensors. The participant and the experimenter were in the same room and could communicate directly, as shown in Figure 5.2.

Participants were invited to the experimental room and explained the task. They were told that they would experience three environments each having different tasks (as mentioned in section 5.2.2) and they would do the tasks collaboratively with the experimenter. They were asked to wear the Zephyr physiological sensors on their chest underneath their clothing. They were told that both of the collaborators would get audio-haptic feedback of each others' real-time HR. Then they filled out the demographic and baseline questionnaires. Before the Furniture Arrangement and Escape Room games they were informed about the interactions using the Vive controllers and they had a chance to practice using it before starting those conditions.

We purposefully designed the experiment to have the same experimenter acting as one collaborator in all sessions with all participants. To minimise any experimenter bias, the experimenter followed a set of scripted dialogues that he rehearsed beforehand. However, based on the responses of the participants, the conversations in each session may be slightly different but the experimenter was careful not to let it deviate from the intended pattern. This helped us avoid any confounding effect that unregulated conversation between two participant collaborators might have caused. While this is a limitation of the experimental design that prevented us from doing any meaningful conversation analysis, it did allow us to ensure that the differences in subjective and physiological responses were only affected by the manipulated independent variables.

After performing each of the tasks, the participants were asked to fill out the subjective questionnaires and we allowed them to take a rest between each task. We also mentioned that they could leave the experiment anytime in case of any discomfort. After the experiment, participants were thanked for their time and given a chocolate gift. The entire experiment took 45 minutes on average per participant to complete.

TABLE 5.1: Mean and standard deviation values at baseline.

Feedback	Age	Positive Affect	Negative Affect	Ratio	Valance	Arousal	Dominance	Exp. with VR
ON *(n=9)*	31.7 (7.5)	23.8 (7.2)	12.3 (3.8)	1.9 (0.6)	2.3 (0.9)	3.2 (1.5)	2.6 (0.7)	5.7 (1.2)
OFF *(n=9)*	30.1 (6.3)	24.4 (6.6)	11.7 (3.9)	2.2 (0.8)	2.4 (0.9)	3.8 (0.7)	3.2 (0.5)	5.0 (1.7)
Overall *(n=18)*	30.9 (6.8)	24.1 (6.7)	12 (3.6)	2.1 (0.7)	2.4 (0.8)	3.5 (1.2)	2.9 (0.7)	5.3 (1.5)

5.2.4 Hypotheses

Before conducting the experiment we postulated the following hypotheses.

- **H1:** The HR feedback ON group will report increased Social Presence and a higher perception of Inclusion of Other in the Self Scale (IOS) than the feedback OFF group. This is because getting this feedback will make the collaborators more aware of each other.

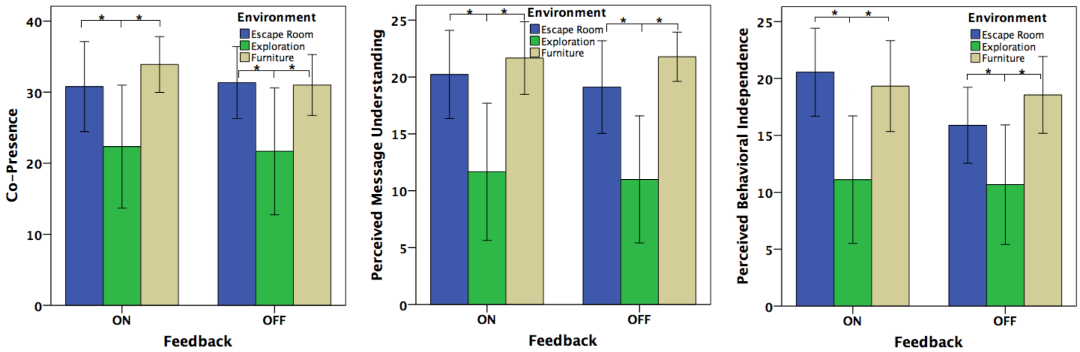
- **H2:** The exploration environment will cause less Social Presence than other environments because it does not require active collaboration between participants.

- **H3:** The HR feedback ON condition will cause a higher positive affect and higher ratio of positive affect/negative affect (PA/NA Ratio) than the feedback OFF condition.

- **H4:** The HR feedback ON condition will cause higher arousal and dominance in the SAM questionnaire than the feedback OFF condition.

5.2.5 Participants

In this mixed-factorial experiment we recruited 18 participants (2 female) and distributed in two equally matched groups (nine participants in each group). Table 5.1 provides more details about the participants. Except for one, all participants had prior experience with VR. Thirteen participants reported that they regularly collaborate with others in their everyday life. Thirteen participants also reported that they believe a person's HR indicates their emotional state.



(a) Co-Presence (b) Perceived Message Understanding (c) Perceived Behavioural Independence

FIGURE 5.3: Results from Social Presence Questionnaire. Whiskers represent $\pm 95\%$ confidence interval. *Represents a significant difference [26].

5.3 Results

We have found that providing real-time HR feedback made participants feel the presence of the collaborator more and helped them feel that they better understood their collaborator's emotional state. When measuring the change from the baseline, it also helped to reduce the negative affect more than when the HR feedback was not given. HR feedback also made the participants feel more dominant when performing the task. The exploration environment was the least emotionally arousing among all virtual environments in this study.

We ran a mixed-factorial ANOVA analysis to analyse the data for each dependent variable using the SPSS software (version 21). Mauchly's test of Sphericity was used to test the assumption of Sphericity for the within-subjects variable (Collaboration Environment) and where the data did not meet the assumption of Sphericity we have used the Greenhouse-Geisser adjustments. Below we first present the results of the subjective data and then the objective data. Despite having 18 participants (nine in each group), all of our ANOVA analyses reported high observed powers (above 0.9) in most cases, which indicates that the analyses are reliable.

5.3.1 Social Presence

The Social Presence questionnaire was analysed in four sub-scales as described below, and in Figure 5.3 and Table 5.2.

Co-Presence: The data showed that the type of environment had a significant effect on co-presence—F(1.45, 23.17)=11.76, p=0.001, η_p^2=0.42, observed power (OP)=0.96. A Post-hoc test with Bonferroni adjustment revealed that people in the Exploration Environment felt significantly less co-presence than in the two other environments (Figure 5.3(a)), and there was no difference in co-presence between the Escape room and Furniture environments. There was no effect of HR feedback on co-presence.

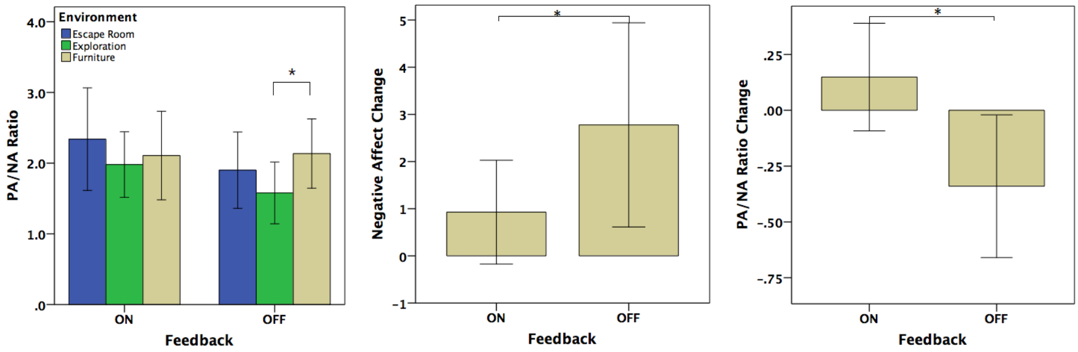
Attention Allocation: For attention allocation there was no significant effect of any of the independent variables.

Perceived Message Understanding: We noticed a significant effect of Environment on perceived message understanding—F(1.42, 22.8)=17.8, $p < 0.001$, η_p^2=0.053, OP=0.99. A post-hoc test showed that participants felt that they had significantly less message understanding in the Exploration Environment (Figure 5.3(b)). We did not find any other significant differences between the other environments.

Perceived behavioural Independence: The Environment had a significant effect on perceived behavioural independence—F(1.28, 20.5)=16.7, $p < 0.001$, η_p^2=0.51, OP=0.99. Participants in the Exploration Environment felt that they

TABLE 5.2: Mean and standard deviation values of responses for the Social Presence Questionnaire, Positive and Negative Affect Schedule (PANAS), and Inclusion of other in the Self (IOS) scale.

Feedback	Environment	Social Presence				PANAS			IOS
		Co-Presence	Attention Alloc.	PMU	PBI	PA	NA	Ratio	
ON		29 (9.63)	22.26 (4.64)	17.85 (7.23)	17 (7.12)	26.96 (9.18)	13.26 (4.78)	2.14 (0.78)	3.3 (1.73)
	Escape Room	30.78 (8.24)	21.89 (4.76)	20.22 (5.04)	20.56 (5.03)	26.44 (9.18)	11.78 (2.82)	2.34 (0.94)	3.67 (1.58)
	Exploration	22.33 (11.26)	23.11 (5.42)	11.67 (7.84)	11.11 (7.29)	28.56 (10.1)	14.67 (4.61)	1.98 (0.6)	2.67 (2.06)
	Furniture	33.89 (5.11)	21.78 (4.09)	21.67 (4.15)	19.33 (5.2)	25.89 (9.13)	13.33 (6.36)	2.11 (0.82)	3.56 (1.51)
OFF		28 (9.24)	23.52 (4.07)	17.3 (7.01)	15.04 (6.1)	25.04 (6.73)	14.44 (5.71)	1.87 (0.66)	3.7 (1.64)
	Escape Room	31.33 (6.6)	24.78 (4.24)	19.11 (5.3)	15.89 (4.34)	26 (7.47)	14.44 (4.59)	1.9 (0.7)	4.22 (1.39)
	Exploration	21.67 (11.63)	24.33 (4.9)	11 (7.26)	10.67 (6.84)	23.22 (6.22)	16.11 (7.29)	1.58 (0.57)	2.44 (1.88)
	Furniture	31 (5.59)	21.44 (2.13)	21.78 (2.82)	18.56 (4.39)	25.89 (6.86)	12.78 (5.07)	2.14 (0.64)	4.44 (0.73)



(a) PA/NA Ratio (b) NA Change from Baseline (c) PA/NA Ratio Change from Baseline

FIGURE 5.4: Results from the Positive and Negative Affect Schedule (PANAS). PA=Positive Affect; NA=Negative Affect. Whiskers represent $\pm 95\%$ confidence interval. *Represents a significant difference [28]

had significantly less behavioural independence than in the two other environments (Figure 5.3(c)). There was no other significant difference.

5.3.2 Positive and Negative Affect Schedule

For the PANAS scale we did not notice any significant effect of Collaboration Environments or HR feedback on either positive or negative affect. However, we noticed a significant effect of Environments on PA/NA ratio—F(2, 32)=3.4, $p = 0.001$, η_p^2=0.51, OP=0.99. The ratio was significantly higher for the Exploration than the Furniture arranging environment (Figure 5.4(a)).

Change from Baseline: We also collected PANAS data at the baseline. For this analysis we averaged the PANAS scores from the three environments and compared with the baseline score using an independent sample t-test. For positive affect, we did not notice any significant effect of the HR feedback on change of positive affect from baseline. For negative affect, we noticed that the negative affect score was significantly increased for HR feedback OFF group than the ON group—t(16)=-1.8, $p < 0.05$ (Figure 5.4(b)). For the ratio of PA/NA we noticed that the ratio significantly increased in the case of HR feedback ON group than for the OFF group—t(16)=-1.8, $p < 0.01$ (Figure 5.4(c)).

5.3.3 Inclusion of Other in the Self (IOS)

We noticed a significant effect of collaboration environment in the IOS ratings—F(2, 32)=8.1, $p = 0.001$, η_p^2=0.37, OP=0.94. A post-hoc analysis showed that the Exploration condition had a significantly lower IOS score than the two other environments (Table 5.2). There was no other significant difference.

5.3.4 Self Assessment Manikin

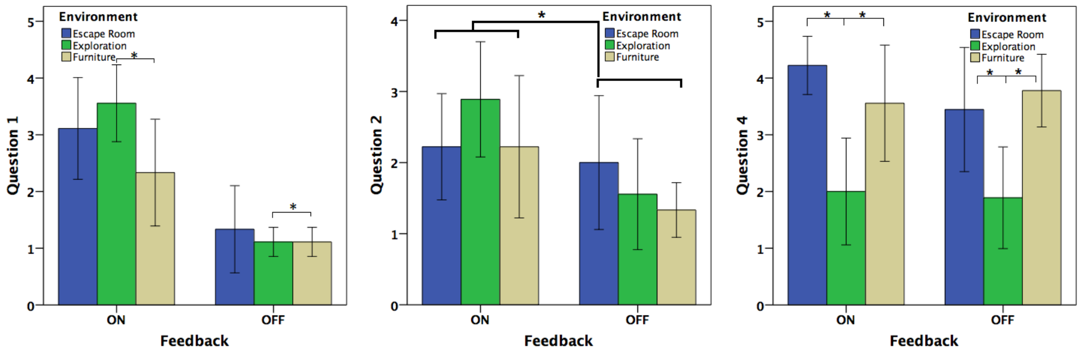
The SAM questionnaire measures three components—valance, arousal, and dominance. For Valance, we noticed a significant effect of Environment—F(2, 32)=4.28, $p = 0.02$, η_p^2=0.21, OP=0.71. A post-hoc test showed that the Exploration condition had a higher average valance score than the Furniture arrangement environment. There was no effect of HR feedback. For Arousal, we noticed a significant effect of Environment—F(2, 32)=3.64, $p < 0.04$, η_p^2=0.16, OP=0.63. Participants felt significantly more aroused in the Furniture arrangement condition than in the Escape room environment. There were no other significant differences (Table 5.3). For dominance, we did not notice any significant effects of any of the independent variables.

Change from Baseline: We did not notice any significant effect of HR feedback on the change in valance and arousal. However, for Dominance we noticed that the average dominance value changed significantly more for the HR feedback ON group than the OFF group—t(16)=2.5, $p = 0.02$.

5.3.5 Additional Questions

We asked four additional questions of the participants after each environment (Figure 5.5 and Table 5.3).

Q1: How strongly did you feel the other person's presence during the task? We noticed a significant effect of Environment—F(1.4, 22.45)=4.31, $p = 0.038$, η_p^2=0.21, OP=0.59. A post-hoc test showed that in the case of the Furniture arrangement environment participants felt the presence of the collaborator significantly more than in the Exploration Environment. There



(a) Q1 (b) Q2 (c) Q4

FIGURE 5.5: Results from Subjective Questions. Whiskers represent ±95% confidence interval [28]

was also a significant main effect of HR feedback—F(1, 16)=28.8, $p < 0.001$, η_p^2=0.64, OP=0.99, where participants in the HR feedback ON group reported feeling the presence of their collaborator more than in the OFF group. There was a significant interaction effect of $Heart\ Rate\ feedback \times Environment$—F(1.4, 22.45)=3.8, $p = 0.05$, η_p^2=0.19, OP=0.54 (Figure 5.5(a)). In the Exploration Environment participants felt the presence of the other collaborator more with HR feedback ON than what they felt when it was OFF.

Q2: How much did you feel the other person's emotional state during the task? We noticed a main effect of HR feedback—F(1, 16)=5.6, $p < 0.03$, η_p^2=0.26, OP=0.6, where participants in the HR feedback ON group reported feeling the collaborator's emotional state more than in the OFF group (Figure 5.5(b)). There was no other significant result.

Q3: How confused did you get with the HR feedback? This question was

TABLE 5.3: Mean and standard deviation values of responses for Self Assessment Manikin (SAM) and our subjective questions.

Feedback	Environment	SAM			Our Questions			
		Valance	Arousal	Dominance	Q1	Q2	Q3	Q4
ON		2.26 (1.02)	3.22 (0.89)	2.96 (0.9)	3 (1.18)	2.44 (1.12)	1.63 (0.93)	3.26 (1.43)
	Escape Room	1.78 (1.09)	3 (0.87)	2.89 (0.93)	3.11 (1.17)	2.22 (0.97)	1.78 (1.09)	4.22 (0.67)
	Exploration	2.67 (0.71)	3.22 (0.97)	3 (1)	3.56 (0.88)	2.89 (1.05)	1.89 (1.05)	2 (1.22)
	Furniture	2.33 (1.12)	3.44 (0.88)	3 (0.87)	2.33 (1.22)	2.22 (1.3)	1.22 (0.44)	3.56 (1.33)
OFF		2.81 (1.04)	3.15 (1.06)	3.04 (1.06)	1.19 (0.62)	1.63 (0.97)	--	3.04 (1.4)
	Escape Room	2.89 (0.93)	2.78 (0.83)	2.78 (0.97)	1.33 (1)	2 (1.22)	--	3.44 (1.42)
	Exploration	3.22 (1.09)	3.22 (1.2)	3 (1.32)	1.11 (0.33)	1.56 (1.01)	--	1.89 (1.17)
	Furniture	2.33 (1)	3.44 (1.13)	3.33 (0.87)	1.11 (0.33)	1.33 (0.5)	--	3.78 (0.83)

asked only to the HR feedback ON group to understand whether the feedback was confusing them. In general participants reported that the feedback was not confusing with a mean value of 1.6 (SD=0.23). We did not notice any significant effect of environment.

Q4: How much do you think your collaborator helped you in the task? We noticed a significant effect of Collaboration Environment—F(2, 32)=21.75, $p < 0.001$, η_p^2=0.58, OP=1. A post-hoc test showed that participants in the Exploration Environment provided a significantly lower average score than in the other two conditions (Figure 5.5(c)). There was no other significant effect.

5.3.6 Physiological Data

We collected both HR and respiration rate data during the tasks. For HR we noticed a significant main effect of Collaboration Environment—F(2, 32)=3.69, $p = 0.03$, η_p^2=0.19, OP=0.64. A post-hoc test showed that participants in the Exploration Environment (M=84.6, SD=12.5) had a significantly higher HR than in the Furniture arrangement environment (M=83.4, SD=18.4) (Figure 5.6). There were no other significant effects. We did not notice any significant effects of either variable on respiration rate.

5.4 Discussion

We had four hypotheses before starting the experiment. In this section, we will discuss the results in relation to these hypotheses and further analyse their implications.

Our first hypothesis stated that the participants sharing HR feedback (the ON group) will report increased Social Presence and higher perceived IOS than the feedback OFF group. This is because getting this feedback will make the collaborators more aware of each other. However, our results did not validate this hypothesis as there was no significant effect of HR cue on Social Presence and IOS ratings.

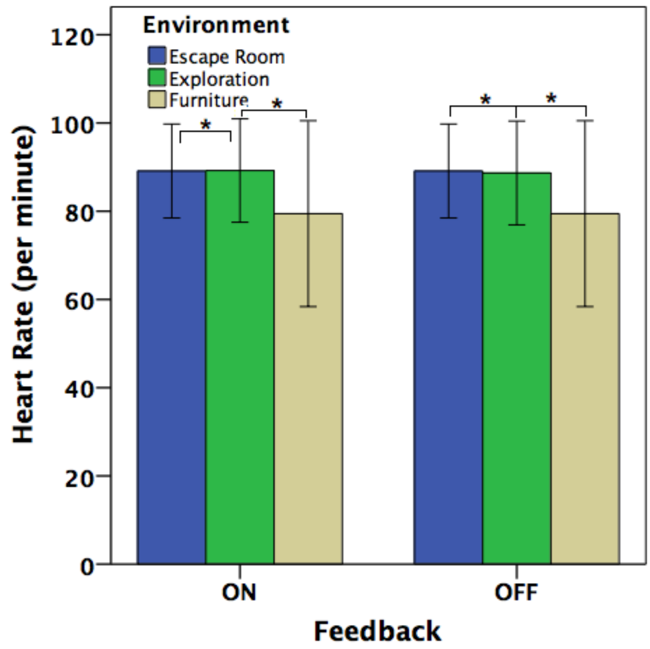


FIGURE 5.6: Participants' HR data during task performance. Whiskers represent ±95% confidence interval. * represents significant difference [28]

We think that participants were more attentive to the task and did not focus as much on the feedback. A few participants mentioned that in the furniture arrangement and escape room game tasks they did not always feel the HR feedback, particularly when they were communicating with the collaborator or interacting with the environment. For example, P15 mentioned *"... did you always give the feedback? I thought I mostly got it when waiting."* This finding was also supported by the interaction effect of $Heart\ Rate\ feedback \times Environment$ noticed for Q1 (Section 4.5), where participants felt the presence of the collaborator more in the case of the exploration environment where interaction and communication were not required. As we did not provide any visual feedback of the HR data, in some cases the feedback was not easily noticeable. Earlier work has shown that multi-sensory cues with visual feedback attract attention in high-load situations [104]. This result is not too surprising given that two of the tasks (the Escape room and Furniture arrangement) required a significant amount of interaction. While our hypothesis was rejected, this finding indicates that adding HR cues did not distract participants from performing the task. Hence, it is important that designers of collaborative VR systems consider the potential task-load when deciding which type of physiological cue could be used. A focused experiment to investigate the relationship between task-load and physiological cue will be helpful.

In our second hypothesis, we predicted that the Exploration Environment would cause less Social Presence than other environments as it does not require active collaboration. This hypothesis was validated by three out of four sub-scales of Social Presence, and found that the Exploration Environment was rated significantly less than the Escape room and Furniture arrangement environments. An earlier study identified that more communication leads to higher Social Presence [134]. As the Exploration Environment did not require any communication and interaction, this environment did not create a high Social Presence compared to the other two environments where communication was necessary. We suggest that if future VR designers want to develop a collaborative application intending to achieve a high Social Presence, they should ensure that the task requires direct communication between the collaborators, and the task should most likely involve synchronous collaboration.

Our third hypothesis stated that the HR feedback ON condition would cause higher positive affect and a higher ratio of positive affect/negative affect (PA/NA Ratio) than the feedback OFF condition. This hypothesis was partially validated. We did not notice any effect of feedback on the task-specific positive or negative affect. However, the feedback ON condition resulted in a significantly lower increase of negative affect from baseline and it resulted in a higher PA/NA ratio increase from baseline than the OFF condition. From the open feedback given by participants after the experiment we noticed that participants in the ON group said that the feedback helped them to notice the presence of the collaborator, which made them feel more social. For example, P12 wrote *"... it is great to feel my collaborator's HR ... makes me feel I am not alone!"* A higher PA/NA ratio indicates that more positive affect was generated per unit negative affect. Overall, both positive and negative affect increased when participants were exposed to the VR environment but adding the HR cue increased this ratio. This is potentially caused by the participants feeling more social, as mentioned by P12. We suggest adding HR cues in collaborative VR environments to make users feel more positive. However, the mode of the feedback needs to be carefully decided based on task load as mentioned above.

The fourth hypothesis predicted that the HR feedback ON condition would cause higher arousal and dominance in the SAM questionnaire than the feedback OFF condition. This hypothesis was only partially validated as we did not notice a main effect on any of the SAM sub-scales for any of the experimental tasks. However, we noticed that the participants' dominance increased from the baseline more in the feedback ON condition than in the feedback OFF condition. This shows a trend that adding HR feedback makes people feel more dominant and, particularly when the feedback is from the other collaborator, it makes them feel safe and social, which consequently increases a sense of dominance.

In addition to these hypotheses, we noticed that the type of environment had a main effect on most of the dependent variables and the Exploration Environment rated relatively poorly compared to the other two environments. However, there was no significant difference between the Furniture arrangement and the Escape room environments. This is expected as the Exploration Environment required little communication or interaction, and involved only looking around. Although we asked participants to be normal and speak as much or as little they wanted, we noticed that except for three of them, in the Exploration Environment all other participants chose to remain silent and only spoke aloud to themselves such as *"oh my god!", "wow!", and "hmm"*. In contrast, the two other environments required active communication. In the Escape room environment, participants talked about where they thought the puzzle pieces were hidden, or in which orientation an object should be placed. In the Furniture arrangement environment, participants talked about which object to select and where exactly to place it. We believe the lack of communication made the Exploration Environment less emotionally appealing to the participants.

5.4.1 Design Guidelines

Based on the results of this experiment, we have formed a pair of design recommendations that will be useful in designing collaborative VR environments.

Provide HR feedback: From our results we noticed that HR feedback resulted in increased dominance, feeling the presence of the collaborator, and understanding the emotional state of the collaborator. Hence, we recommend providing HR feedback in collaborative VR environments where creating empathy between the collaborators is beneficial, such as in training, education, and medical applications.

Encourage more communication and interaction during the task: We noticed that in the Exploration Environment participants scored significantly lower than in the two other environments on the various scales measured here. Based on this finding, we recommend that when designing collaborative environments, more communication and interaction should be encouraged where possible to increase Social Presence and empathy between collaborators.

5.5 Limitations

Our study has some limitations. Firstly, we recruited the participants who are mostly male due to the difficulty of recruiting females on our campus. Secondly, after participants finished the user study, we did not interview them, or get more informal feedback. The interview quotes could be analysed and recorded for our results analysis. Thirdly, our three VR environments all are collaborative, but they are not tense as much as shooting games. In these VR environments, the users' HR is almost the same during the collaboration. In the future, we will design tenser games, which could make it easier to detect the effect of the VR scene on the users' HR.

5.6 Conclusion

In this chapter, we investigated the effects of sharing real-time multi-sensory HR feedback between users in different collaborative virtual environments. Our results identified that compared to the feedback OFF group, the feedback ON group had more dominance when exposed to VR, generated more positive affect for unit negative affect, noticed the presence of the collaborator more, felt the collaborator's emotional state more, and overall was not confused by the feedback. These results show the benefits of providing HR feedback in collaborative VR environments.

We have also identified that the type of collaborative virtual environment influences Social Presence, inclusion of other in the self (IOS) ratings, valance, arousal, and the realization of the presence of the collaborator in the VR environment. Where more active interactions and communications were involved (the Escape room and Furniture arrangement) these effects were more positive than in the environments where such active interactions and communications were not required, such as the Exploration Environment.

Based on the insights of this experiment, we provided two design guidelines for empathic collaborative VR applications. We hope these guidelines will help future researchers and developers.

Our current research has identified a few new research directions that we may pursue next. First, we found that due to the high level of required interaction and communication, potentially causing high task load, in two of the environments participants did not focus on the audio-haptic HR feedback. Previous research has shown that in the case of high task loads, visual cues are more perceived than other channels, such as the audio-haptic cues we used [104]. In the future it will be interesting to investigate the effect of different task loads on the HR feedback given through different sensory channels such as haptic, audio, and visual. Second, in this experiment we only provided HR feedback through audio-haptic channels. However, there are other physiological signals such as GSR and respiration rate, for which we did not provide feedback.

Thirdly, it will be interesting to design collaborative interfaces that can adapt to the task load of the environment and provide physiological feedback through appropriate channels for better perception. Finally, one of the limitations of this study is the constant presence of an experimenter in the collaboration tasks. In a future study, it will be interesting to investigate the effects of HR feedback on verbal and gestural communication patterns in different collaborative setups where unregulated communication between multiple collaborators is allowed.

Chapter 6

An Exploration of Sharing Manipulated HR Feedback in Collaborative Virtual Environments

In Chapter 4, we conducted one study to investigate the response when users were exposed to their own manipulated HR feedback. In Chapter 5, we designed two active collaborative VR environments where the user's HR was shared between them. Based on what we have learned in these two chapters, in this chapter we are going to explore the effect of sharing manipulated HR feedback in collaborative virtual environments. This study has been accepted into the ISMAR 2019 conference as a full paper.

6.1 Introduction

This chapter explores how manipulating physiological feedback can change the emotional experience for people in a shared VE and this work extends my work in Chapter 5 and explores what happens when one user is hearing a manipulated HR cue of another user in the same VR experiences. For example, what happens when the player's HR is normal, but the audio-haptic cue send to the observer is from a sped-up version of the player's actual HR? This is an interesting question because if the observer's experience in VR can be enhanced through manipulation of a player's physiological cues, this could be used as a technique to create a better experience. Our work in Chapter 4 explored this question in a single user setup and found HR manipulation can manipulate certain emotions when experiencing VEs.

6.2 Experimental System Design

In this user study, we designed six VR scenes. Three of them are passive games, called Safari touring. In these three VR scenes, participants were standing on the back of a virtual pickup, which moved on its own without any intervention from the players. The two participants appeared in the VR scenes as two virtual heads. They could rotate their virtual head by rotating their real head to see each other in their HMD, as shown in Figure 6.2(f). Each Safari VR experience is about 4 minutes in length. We designed the other three VR scenes to be active and a zombie shooting game. In these VR scenes, the two participants need to work together to shoot zombies and spiders coming at them from four different directions (Figure 6.2(c)). We used Photon Engineer[1] to make the Zombie shooting game into a networked game. The two participants could see each other's head and the virtual guns they held in their hands. We used the HTC VIVE[2] HMD, controllers and tracking system to help participants experience the VR scenes.

When two participants were playing the games, they could hear each other's real-time heartbeat. We used the Zephyr BTLE BioModule Device to capture the real-time HR (see Figure 7.1). The sensor was strapped around the participant's chest. To share HR, we set up a server to collect the HR data of one participant via Bluetooth Low Energy (BLE) and streamed the data to the computer connected to the other participant's HTC Vive through the UDP protocol. For example, the server collected the HR data from the sensor on participant 1 and then streamed the data to PC2 and participant 2. The HR signal acquired from the participants was fed into Unity. Within Unity a script

[1]https://www.photonengine.com/
[2]https://www.vive.com/

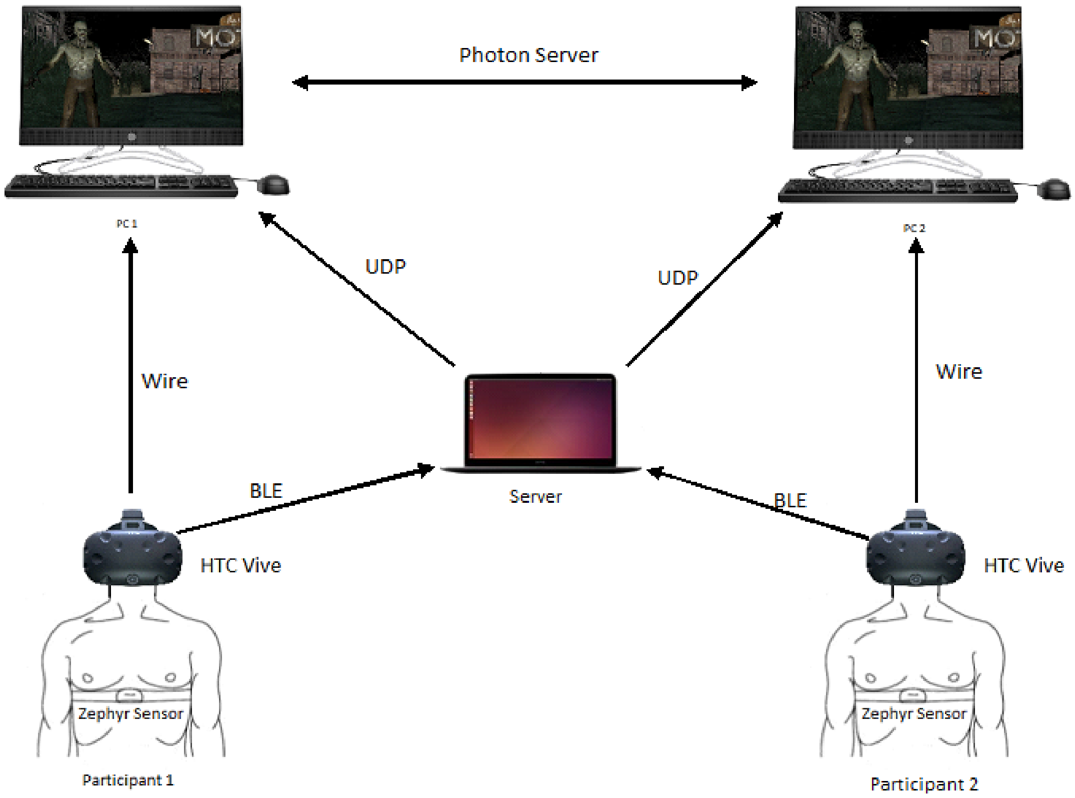


FIGURE 6.1: The experimental system [27]

analysed the incoming HR data and sonified it by playing a pre-selected audio clip at intervals matching the participants' HRs. The script also analysed the HR and used it to implement haptic feedback with different vibration strength on the HTC VIVE controllers according.

6.3 User Study

To explore the effects of providing manipulated HR feedback in collaborative VEs—where both collaborators will get the feedback of the other collaborator (and not of their own)—we conducted a *within-subjects* user study with 24 participants grouped into 12 pairs.

6.3.1 Independent Variables

There were two independent variables in this experiment—Manipulation Level and Environment Type, as described next. Being a within-subjects study,

(a) (b) (c)

(d) (e) (f)

FIGURE 6.2: Representative scenes of the test environments. The active shoot to survive game (a-c) and passive jungle safari game (d-f). In both environments, the location and orientation of the collaborator was visualised by a unisex head model (f) [27].

all participants experienced all levels of both of the independent variables. The presentation order of the independent variables was counterbalanced.

Manipulation Level -20%, 0%, +20%

In a previous study with non-collaborative tasks, it was found that $\pm 30\%$ manipulation of HR feedback was easily identifiable by the participants. However, $\pm 15\%$ went unnoticed [28]. Learning from that study and after our own pilot study we identified that manipulation level of $\pm 20\%$ was noticeable by participants. Hence, we had three levels of manipulation -20%, 0% (real), and $+20\%$. To collect the real-time HR data we used Zephyr HR sensors that participants wore on their chests.

All of the HR feedback was provided using real-time audio-haptic channels, following our study in [20]. Haptic feedback was provided using the HTC Vive controllers and the audio feedback was provided using Logitech noise-cancelling headphones. One important fact to note is that the participants were unaware of the manipulation. They were told that the feedback they were getting was real and in real time. This was done to ensure that the participants were not primed and respond with that knowledge in mind.

Collaborative Environments Active (shooting) and Passive (safari)

We designed two different collaborative environments with different levels of interactivity. We were interested in identifying what effect do interactions have on the perception of the manipulated feedback? Using the Unity 3D game engine, we created three similar versions for each of the environments to properly counterbalance with the manipulation levels and to avoid learning effects. All of the VR experiences lasted for four minutes. In both of the environments, we asked participants to talk freely with each other as much as they wished.

Active (shoot to survive):
In this environment, participants were placed in an abandoned industrial area at night where multiple zombies were attacking them (Figure 6.2(a-c)). They had two revolvers, one in each hand, to shoot at the zombies to survive. There were two participants (players) shooting at the zombies and if one player died the other would also die, hence they had to help each other and communicate. The zombies could come and attack from any direction. However, when they appeared they were visible from a distance giving enough time to identify and shoot. We supplemented the environment with appropriate sound effects. Players were able to see each other in the environment as a virtual unisex head model. The orientation and location of that model was updated in real time based on the players' movements in the real world.

We designed the environment in a way that none of the players died in the virtual world as we wanted all participants to experience the VEs for the entire four minutes. However, participants were not aware of the fact. We created three versions of the environment where the location was slightly different but the lighting conditions and number of attacking zombies were the same.

Passive (jungle safari):
The passive experience was based on a jungle safari with various animals

moving around in the environment and supplemented with suitable sound effects (Figure 6.2(d-f)). Both participants were tourists and placed in a standing position on the back of a virtual car moving along without any interaction from the players. Most of the visual effects of interest were presented in front of the participants' eyes within a $200°$ horizontal field of view. However, there were sound effects that originated from behind the participants using spatial sound playback. Similar to the earlier environment, a virtual unisex head model was provided to indicate the location of the collaborator.

In the physical world, both of the participants were standing with a hand-rest in front to maintain balance, if needed. They were allowed to look around and rotate their heads to experience the VE at will. However, they were not allowed to walk as we wanted to avoid any elevated physiological signals due to locomotion.

6.3.2 Dependent Variables

Our main goal of the experiment was to identify the effects of manipulated HR feedback on self-perception of emotions and the emotions of the collaborator. We were also interested in identifying how the collaboration was affected due to the manipulated feedback. As such we collected subjective data through four validated instruments. First, the Positive and Negative Affect Schedule (PANAS) [129] was used to collect the participant's emotional state and we also asked participants to rate their collaborator's emotional state as also using the same survey. Second, we used the Inclusion of the Other in Self (IOS) scale to measure how the participants felt connected to their collaborator. Third, we used the Social Presence Questionnaire (SPQ) [47] to measure the overall Presence felt in the collaborative tasks. We measured participants' general emotions and arousal using the self-assessment manikin [13]. As an objective variable we collected the participants' raw HR data.

6.3.3 Task and Procedure

The experimental environments were collaborative, so the tasks were done in pairs. In the shooting task, participants had to look for zombies coming from all directions and shoot them to survive. They also had to help the other collaborator so that neither of them died. Overall, this environment required more interaction with the environment and the other collaborator. Hence, we classify this task as an active task. The other task–safari—simply required participants to look around and experience a virtual jungle safari together. There was no interaction with the environment beyond just looking around and interaction with the other collaborator was not required. We term this as a passive task. During all of the tasks there was a continuous HR feedback of the other player provided. All participants were categorically told that the feedback they were receiving was that of the other collaborators and not their own and that the feedback was in real time.

Each pair of participants had to go through all environments and HR manipulation levels. Hence, they had to perform experimental tasks under six different conditions. We first welcomed the participants and explained the experiment. They then signed a consent form and wore the sensor on their torso underneath their clothes. Then we asked the participants to rest for two minutes and start filling out a demographic questionnaire. They also filled out the PANAS scale to establish a baseline measure. Following that, they started performing the first experimental task. After each task they had to answer a set of questionnaires as mentioned in Section 6.3.2. This allowed participants to calm down from the earlier task. We also asked participants to rest for as long as they wanted before starting the next task. The process was repeated six times. One thing to note is that both participants in each pair responded to the same set of questions separately. In the end, we debriefed the participants and told them about the manipulation. Participants were allowed to leave the experiment anytime without giving us any reason. Overall, the experiment took almost two hours per pair on an average to complete.

6.3.4 Hypotheses

Before running the experiment we had a few hypotheses, as described below.

- **H1:** The active environment will cause the participant to have a higher HR than the passive environment, as this environment requires more interaction and physical movement.
- **H2:** Dey et al. [28] noticed that real feedback causes less intensity of five emotions in the PANAS scale – interested, excited, scared, nervous, and afraid. We expected the same emotions to be affected in our study as well.
- **H3:** As the higher HR perceptually relates to higher stress [98] and individuals under higher stress seek social presence [32], we expected in the higher manipulation levels participants will have a higher social presence.
- **H4:** For the same reason as H3, we also expected to have a higher IOS rating at the $+20\%$ manipulation level than the other two levels.
- **H5:** We expected that participants will feel that they and their partners have the highest valance and arousal at the +20% manipulation level according to the finding in Chapter 4.

6.3.5 Participants

We recruited 24 participants (5 females) in this study through social media advertisement, personal contacts, and university mailing lists. The participant ages ranged from between 19 and 46 years (M=30.2, SD=6.7). At the beginning we asked participants to rate their experience with VR out of ten. Our participant cohort was moderately experienced with VR (M=5.8, SD=2.9). They reported doing work in collaboration with colleagues and friends in real life (M=6.3, SD=2.5). They moderately agreed to the statement "Someone's HR indicates that person's emotional state" (M=5.2, SD=0.8). All of the participants

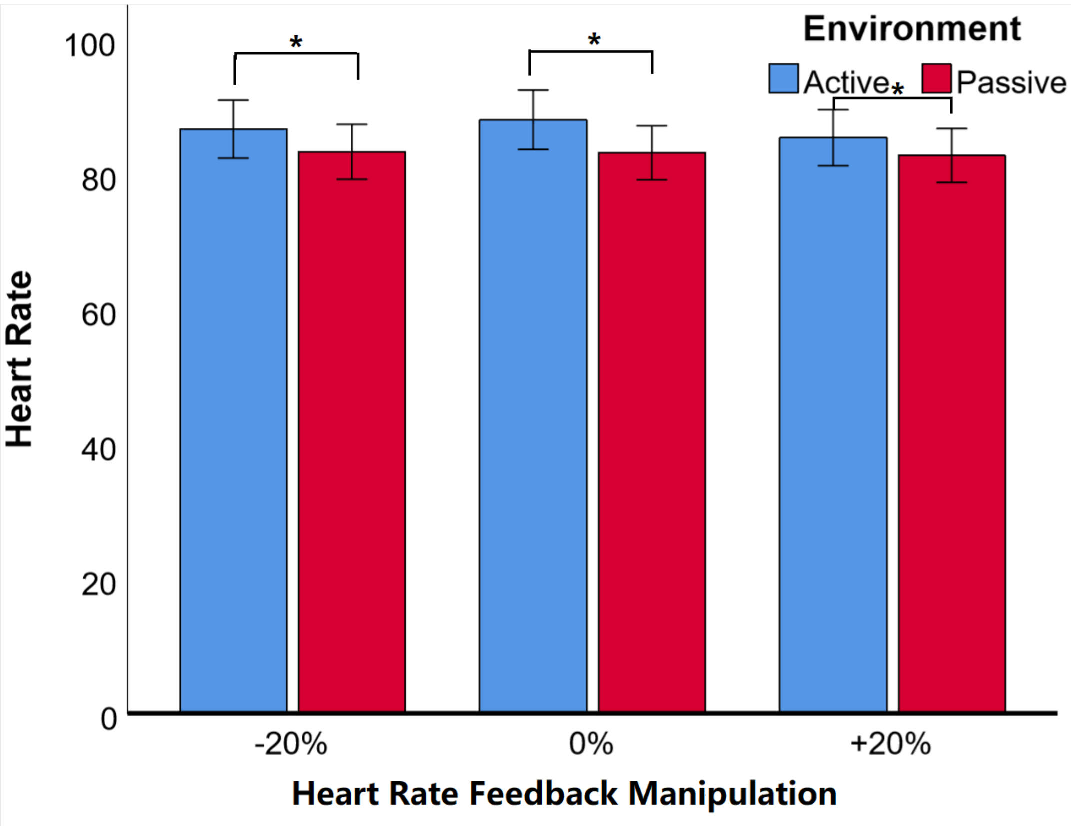


FIGURE 6.3: HR during the experimental tasks. Whiskers represent $\pm 95\%$ confidence interval [27].

had normal or corrected to normal vision. We created 12 pairs of participants to perform the experiment, with people in five pairs previously knowing each other. Prior to conducting the experiment we calculated the required sample size to achieve an acceptable power in the analysis using G*Power version 3.1. We found that to achieve a power of 0.9, 24 participants were required. Hence, our sample size is sufficient for the experimental validity. Participation was voluntary and each of the participants was paid a $20 gift voucher for their participation in the study.

Over the whole experiment, we had 24 (participants) $\times$ 3 (manipulation levels) $\times$ 2 (environment) = 144 data points.

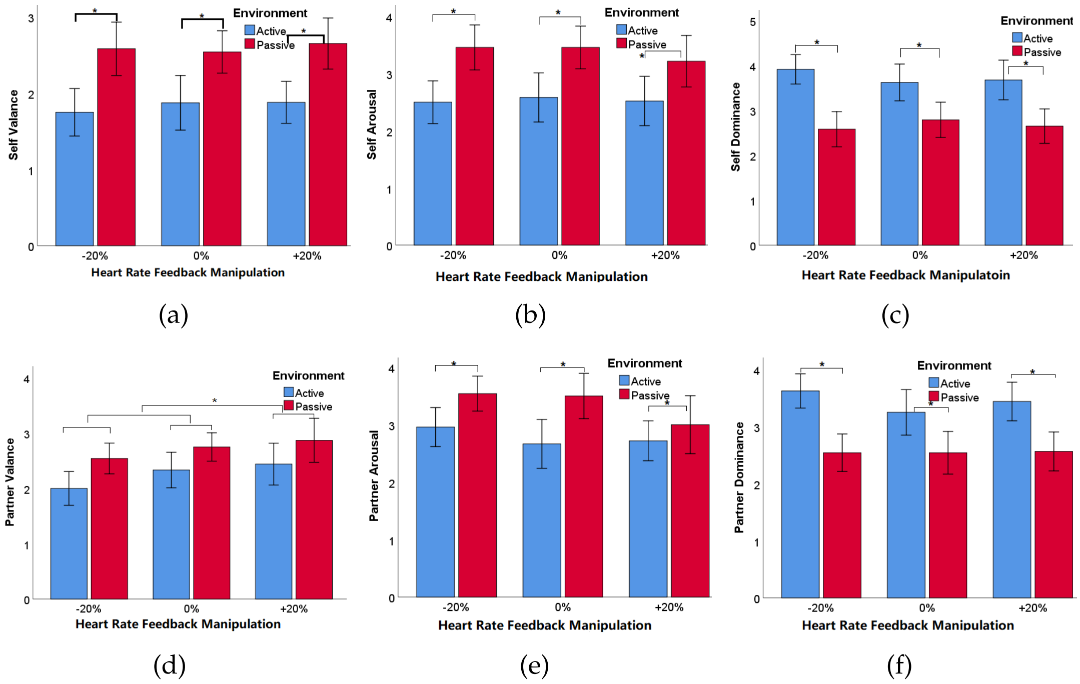


FIGURE 6.4: Self Assessment Manikin ratings. Whiskers represent $\pm 95\%$ confidence intervals [27].

6.4 Results

6.4.1 Heart Rate

To analyse the effects of the independent variables on the participants' real HR we used a two-way repeated measure analysis of variance (ANOVA). We found a significant main effect of the environment—F(1, 23)=7.1, $p = .014$, η_p^2=.24, Observed Power (OP)=.72 (Figure 6.3 and Table 6.1). In the active environment HR was significantly higher than in the passive environment. We noticed a trend towards the strong effect of the manipulation levels, although it was not statistically significant—F(2, 46)=2.6, $p = .08$, η_p^2=.1, Observed Power (OP)=.49. Interestingly, in both environments, +20% manipulation had the lowest real HR. There was no significant interaction effect.

TABLE 6.1: The mean and standard deviation values of Social Presence, inclusion of other in self scale (IOS), and HR.

Manipulation	Environment	Social Presence					IOS	Heart Rate
		CP	AA	PMU	BI	Overall		
-20%	Active	33.9 (7.4)	-7.3 (8.2)	18.8 (5.7)	18.5 (5.4)	63.9 (20)	4.6 (1.3)	86.8 (10)
	Passive	26.5 (8.4)	-11.7 (7.2)	13.1 (6.6)	10.4 (5.4)	38.4 (17.6)	2.5 (1.2)	83.4 (9.4)
0%	Active	33 (8.5)	-8.5 (6.6)	16.6 (4.7)	18.3 (4.5)	59.4 (16.4)	4.3 (1.4)	88.2 (10.2)
	Passive	26.9 (9)	-11.2 (8.7)	13.3 (6.9)	12.2 (5.9)	41.2 (23.3)	2.6 (1.4)	83.3 (9.3)
20%	Active	34 (7.7)	-9.9 (6.7)	17.2 (5.7)	17.8 (5.2)	59.2 (17.9)	4.7 (1.6)	85.5 (9.6)
	Passive	25.9 (8.2)	-11.6 (7.3)	12.1 (6.7)	10.3 (6.3)	36.6 (22.3)	2.3 (1.2)	82.9 (9.3)

TABLE 6.2: The mean and standard deviation values of the SAM scale ratings for self and the partner.

Manipulation	Environment	SAM (Self)			SAM (Partner)		
		Valance	Arousal	Dominance	Valance	Arousal	Dominance
-20%	Active	1.7 (0.7)	2.5 (0.8)	3.9 (0.7)	2 (0.7)	2.9 (0.8)	3.6 (0.7)
	Passive	2.5 (0.8)	3.4 (0.9)	2.5 (0.9)	2.5 (0.6)	3.5 (0.7)	2.5 (0.7)
0%	Active	1.8 (0.8)	2.5 (1)	3.6 (0.9)	2.3 (0.7)	2.6 (1)	3.2 (0.9)
	Passive	2.5 (0.6)	3.4 (0.8)	2.7 (0.9)	2.7 (0.6)	3.5 (0.9)	2.5 (0.8)
20%	Active	1.8 (0.6)	2.5 (1)	3.6 (1)	2.4 (0.9)	2.7 (0.8)	3.4 (0.8)
	Passive	2.6 (0.7)	3.2 (1)	2.6 (0.8)	2.8 (0.9)	3 (1.1)	2.5 (0.7)

6.4.2 Self-Assessment Manikin (SAM)

Data in the SAM questionnaire is non-parametric and ordinal, hence, we used the Wilcoxon Signed Ranks test for the Environment variable and Friedman's test for the manipulation variable. We noticed a significant effect of collaborative environments on valance (Z=-4.9, $p < .001$, $passive > active$), arousal (Z=-5.1, $p < .001$, $passive > active$), and dominance (Z=-5.1, $p < .001$, $passive < active$) when participants rated their own experience. We noticed similar significant effects when participants rated their partner—valance (Z=-3.3, p=.001, $passive > active$), arousal (Z=-3.3, p=.001, $passive > active$), and dominance (Z=-4.6, $p < .001$, $passive < active$). We also measured the difference in ratings between when they rated themselves and their partner. We only noticed a significant effect on valance (Z=-2.4, $p = .015$, $passive > active$) meaning that in more cases of active environment than passive environment, participants rated that their partner had more positive emotions than themselves (Table 6.2).

For the manipulation levels, we did not notice any significant effects. However, there was a trend towards significance in partner valance (χ^2(2)=4.7,

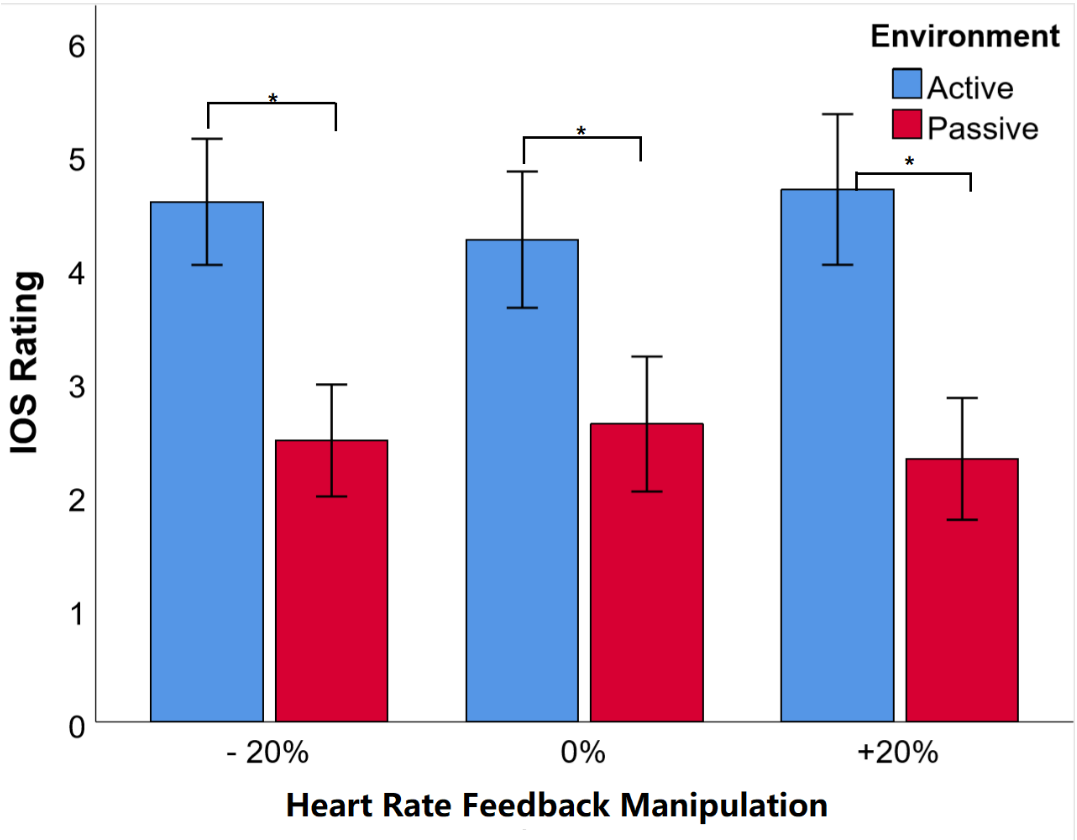
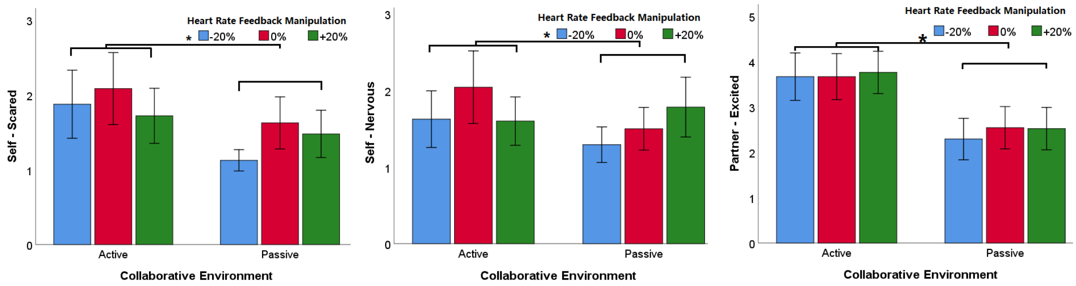


FIGURE 6.5: Inclusion of other in self scale. Whiskers represent $\pm 95\%$ confidence interval [27].

p=.09) and partner arousal (χ^2(2)=5.4, p=.06). In case of partner valance (Figure reffig:sam(d)), participants perceived their partner to be the most positive emotionally at the +20% manipulation level followed by the 0% and -20% levels. In the case of arousal (Figure 6.4(e)), the effect reverses and participants perceived their partner to be most aroused at the -20% manipulation level followed by the 0% and +20% levels.

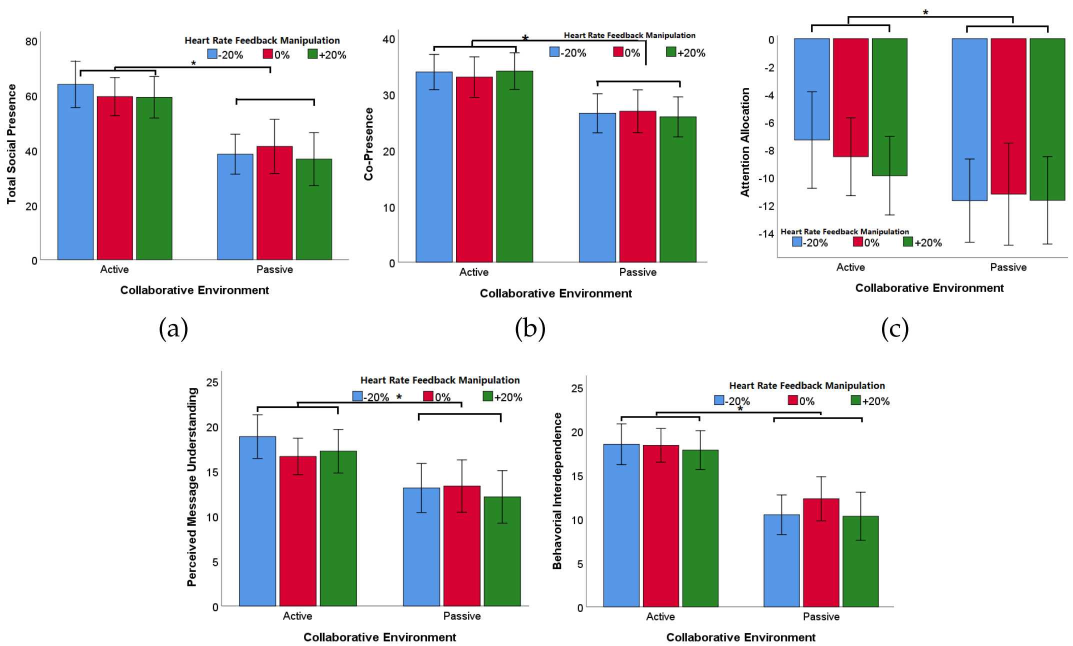
6.4.3 Inclusion of The Other in Self Scale (IOS)

As the data for the IOS scale is ordinal and non-parametric in nature we ran two separate Friedman's test for each of the independent variables. We found a significant effect of the environment on the IOS ratings—χ^2(1)=33.1, $p < .001$ (see Figure 6.5 and Table 6.1). In the active shoot and survive environment participants felt more connected to each other than in the passive



(a) (b) (c)

FIGURE 6.6: Positive and negative affect schedule ratings. Whiskers represent ±95% confidence intervals [27].



(a) (b) (c)

(d) (e)

FIGURE 6.7: Ratings for social presence. Whiskers represent ±95% confidence intervals [27].

TABLE 6.3: Mean and standard deviation values of Positive and Negative Affect Schedule (PANAS) ratings when rated for self.

Manipulaiton	Environment	PANAS (Self)						
		Interested	Excited	Scared	Nervous	Afraid	PA	NA
-20%	Active	4.2 (1.1)	3.7 (1.3)	1.8 (1)	1.6 (0.8)	1.5 (0.9)	36 (10.8)	15.8 (6.1)
	Passive	3 (1.2)	2.5 (1.2)	1.1 (0.3)	1.2 (0.5)	1.1 (0.3)	23.8 (10.2)	12 (3.3)
0%	Active	4.1 (1)	3.7 (1.2)	2 (1.1)	2 (1.1)	1.7 (1.2)	36 (10.6)	16.8 (6.8)
	Passive	3.1 (1.2)	2.8 (1.3)	1.6 (0.8)	1.5 (0.6)	1.3 (0.6)	25.8 (9.6)	14.1 (4.9)
20%	Active	4.2 (1)	3.8 (1.3)	1.7 (0.8)	1.6 (0.7)	1.5 (1)	35.8 (11.1)	15.7 (5.9)
	Passive	2.9 (1.4)	2.6 (1.1)	1.4 (0.7)	1.7 (0.9)	1.4 (0.7)	24 (9.1)	14.3 4(4.8)

TABLE 6.4: Mean and standard deviation values of Positive and Negative Affect Schedule (PANAS) ratings when rated for the partner.

Manipulaiton	Environment	PANAS (Partner)						
		Interested	Excited	Scared	Nervous	Afraid	PA	NA
-20%	Active	1.7 (1)	4 (1.1)	3.6 (1.2)	1.4 (0.7)	1.3 (0.7)	34.5 (9.9)	14.7 (5.2)
	Passive	1.2 (0.6)	2.9 (1.1)	2.2 (1)	1.3 (0.6)	1.1 (0.3)	22.8 (9)	11.8 (2.9)
0%	Active	2.1 (1.2)	3.9 (1)	3.6 (1.2)	1.8 (0.9)	1.8 (1.2)	33.7 (10.3)	17 (8.1)
	Passive	1.3 (0.7)	3.1 (1.2)	2.5 (1.1)	1.3 (0.6)	1.3 (0.7)	24.4 (8.9)	13.2 (4.8)
20%	Active	1.7 (0.9)	4 (1)	3.7 (1.1)	1.7 (0.8)	1.4 (1)	34 (10.2)	15.5 (5.6)
	Passive	1.5 (0.8)	2.9 (1.3)	2.5 (1)	2 (1)	1.5 (0.8)	23.3 (8.5)	14.6 (6)

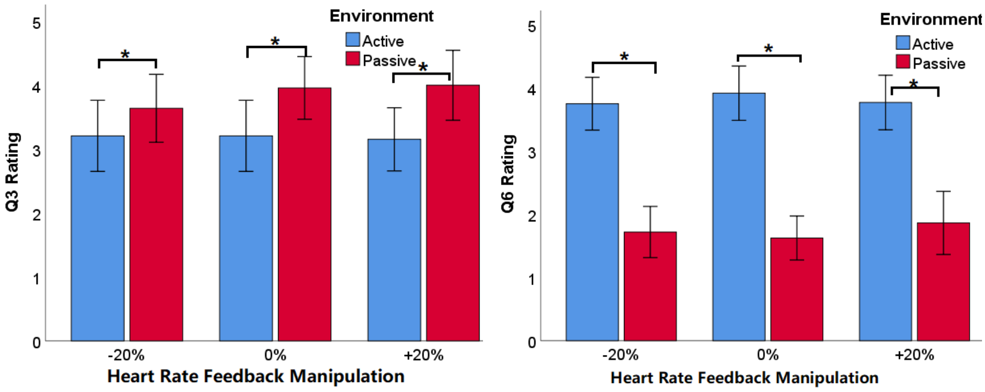
safari environment. However, we did not notice a significant effect of HR manipulation.

6.4.4 Positive and Negative Affect Schedule (PANAS)

Using a set of repeated measure ANOVAs, we did not find a significant effect of either HR manipulations levels or environment on the overall positive affect (PA) and negative affect (NA) as rated for self (Table 6.3) and the partner (Table 6.4). However, we found a significant correlation between PA and NA when reported for self—PA = 13.23+1.15×NA, $p < .001$ and when reported for the partner—PA = 16.86+.83×NA, $p < .001$. We also noticed that PA and NA were significantly correlated for all levels of both independent variables, where PA was always more than NA.

Analysis of individual emotions and feelings

We then looked at the five individual emotions and feelings—interested, excited, scared, nervous, and afraid. We separately looked at the data when reported for self and for the partner.



(a) (b)

FIGURE 6.8: Ratings for the subjective questions 3 and 6. Whiskers represent $\pm 95\%$ confidence intervals [27].

Reported for self emotions and feeling

We noticed a significant interaction effect of HR manipulation $\times$ environment—F(2, 46)=4.4, $p = .02$, η_p^2=.2, OP=.73 on the feeling of being *scared* (Figure 6.6(a)). A similar interaction effect was noticed for nervousness—F(2, 46)=5.6, $p < .01$, η_p^2=.2, OP=.83 (Figure 6.6(b)). There were no other significant main and interaction effects found.

Reported for partner's perceived emotions and feelings

Participants perceived their partner to be significantly more excited in the active environment than in the passive one—F(1, 23)=5, $p = .035$, η_p^2=.2, OP=.57, which is consistent to our expectation (Figure 6.6(c)). We did not find any other significant effect.

6.4.5 Social Presence

We used the Social Presence Questionnaire by Harms and Biocca [47], and the four sub-scales of the questionnaire which were relevant to our experiment—Co-presence, Attention allocation, Perceived message understanding, and Behavioral interdependence. Along with the sub-scales we have also calculated the total social presence as a sum of these sub-scales. To analyse the data we used two-way repeated measure ANOVAs.

In all cases, we have noticed a significant effect of collaborative environment on the Social Presence and in all scales the active environment was rated better than the passive environment (see Figure 6.7 and Table 6.1). Total social presence—F(1, 23)=44.18, $p < .001$, η_p^2=.66, OP=1; Co-presence—F(1, 23)=44.18, $p < .001$, η_p^2=.66, OP=1; Attention allocation—F(1, 23)=7.64, $p = .01$, η_p^2=.25, OP=.75; Perceived message understanding—F(1, 23)=30.36, $p < .001$, η_p^2=.57, OP=1; Behavioral interdependence—F(1, 23)=47.72, $p < .001$, η_p^2=.66, OP=1. There were no other significant differences.

6.4.6 Other Subjective Questions

We asked the following six subjective questions, which participants answered on a five-point Likert scale with 1 = *Not at all* and 5 = *Very*, and a higher value indicated positive response except for the fifth question where the above scale was reversed.

1. How much attention did you pay to your partner's HR when in the game?
2. How much do you think that the HR visualisation affected your experience when in the game?
3. How strongly did you feel the other person's HR during the task?
4. How much did you feel the other person's emotional state during the task?
5. How confused did you get with the HR feedback?
6. How much do you think your collaborator helped you in the task?

To analyse the subjective questions we used repeated measure ANOVAs (Figure 6.8). We did not notice any significant difference except for in Q3 and Q6. Question Q3 had a main effect of collaboration environments—F(1, 23)=6.9, $p = .015$, η_p^2=.2, OP=.71, where the passive environment (M=3.86, SD=1.22) received higher ratings than the active environment (M=3.18, SD=1.27), indicating that the participants felt the other collaborator's HR more in the passive environment than the active. Question Q6 had a main effect of collaborative environments—F(1, 23)=87.7, $p < .001$, η_p^2=.8, OP=1, and the active environment (M=3.81, SD=1.01) had higher ratings than the passive environment (M=1.73, SD=0.97) indicating that participants felt that the other collaborator helped them more in the active environment than in the passive environment.

6.5 Discussion

In this section, we discuss the results in relation to the hypotheses. Our first hypothesis was *H1: The active environment will have higher HR than the passive environment.* Our analysis proved this hypothesis to be true. Our active environment required participants to shoot at the zombies and creatures and quickly look around to find them. We also noticed that participants communicated more with each other in this environment. These actions increased their HR. In contrast, the passive environment did not require any bodily movement. Although, users were allowed to look around and communicate. However, they did not communicate as much as in the passive environment. P12 mentioned *"... the zombie game was more fun and I wanted to shoot at the zombies and to help my partner. But the safari was a calm experience, which I enjoyed but did not feel as pumped as in the zombie game."* '

It was interesting to find that the physical HR was lower in the +20% manipulation level in both environments. In our experiment participants experienced the HR of their collaborator. A higher HR provides a perception of an aroused state of the autonomic nervous system or a state that is commonly experienced while being under threat or feeling stressed [124]. This might have caused participants to feel that their partners were vulnerable and chances of their defeat is higher, which induced a social stress resulting in their own HR to be dropped [108].

Our second hypothesis, based on an earlier work by Dey et al. [28], stated that *H2: five relevant emotions in particular will be affected by the manipulated HR feedback—interested, excited, scared, nervous, and afraid*. We asked the participants to rate their own emotions and that of their partner's using the PANAS scale. Our second hypothesis was partially accepted as there was an interaction effect between HR manipulation and the environments for the two emotions—scared and nervousness. For the feeling of being scared, we noticed a significant difference between the two environments for the -20% manipulation level. However, for other manipulation levels the difference was not significant. We believe that the scary elements in the passive environment were not as profound as it was in the active environment. When participants noticed that their partner's HR was low, indicating that they are relaxed and in control of the experience, they themselves also felt relaxed and less scared. However, the same effect was not seen when they were in the active environment and shooting at the creatures to survive. This could be because they did not pay enough attention to the feedback. A few participants mentioned that they were more focused on the shooting task than the HR feedback. For example, P5 mentioned *"... the shooting was fun and exciting but I am not sure whether I noticed the feedback as it was somehow hidden behind the sounds of gunshots."*

This is an interesting finding as it identifies a need for more thoughtful feedback design based on the task at hand and the environmental elements such as sound and lighting. A salient visual feedback may be more appropriate than audio-haptic feedback in stressful and action-packed environments. We also noticed that the feeling of nervousness gradually increased with the increasing HR feedback in the passive environment but for the active environment 0% had the highest intensity of nervousness. This is possible because in the passive environment participants had more opportunity to experience the feedback and get influenced by it than in the active environment where they needed to pay more attention to the task at hand.

In our third hypothesis, we expected that *H3: higher HR manipulation levels participants will have higher social presence*. This hypothesis was rejected as we did not find a significant main effect of manipulation levels on overall Social Presence or on any of the sub-scales. We believe that this is because participants were not receiving their own HR feedback rather they experienced the HR of their collaborator. Based on previous findings [98, 32] we expected to see that a higher HR would induce higher Social Presence. However, the difference between earlier work and our work was that the feedback in our experiment was of a different individual and not that of the self. From our results, it is clear that a participant getting feedback from their own HR causes different effects than getting feedback of another person's HR. However, we noticed a significant main effect of environment where the active environment resulted in higher Social Presence than the passive environment. This is expected, as the active environment required more communication between the collaborators and surviving the zombie attacks by helping each other.

Our fourth hypothesis expected that *H4: higher HR manipulation levels will cause higher ratings in the IOS scale*. This hypothesis was not supported as there was no significant effect of HR manipulation levels on the IOS ratings. However, we noticed that the active environment caused significantly higher IOS ratings than the passive environment. We believe this is because the task in the active environment required more communication and collaboration to survive, causing participants to feel a closer connection with the collaborator.

Our fifth hypothesis was that *H5: the +20% manipulation level will cause the highest valance and arousal for both the self and partner*. This hypothesis was not supported at the significance levels tested. However, we did notice a strong trend towards significance when rated for partner valence ($p=.09$) and arousal ($p=.06$). For valance, participants perceived their partner to have positive emotion most at the +20% manipulation level. This could be because in the high HR feedback levels participants perceived their partner to be excited and enjoying the experience. P14 explained *"... I think he (the partner) was having a great time as his HR was going up as he was shooting."* For arousal, however, the effect was reversed and participants perceived their partner to have the highest arousal in the -20% manipulation level. The reason for this counter-intuitive effect is unclear and requires further experimentation. Otherwise, for the SAM questionnaire, we noticed that participants thought that they and their partners were more aroused and had higher valance in the active environment than in the passive environment. This is expected, and consistent to earlier findings, as more interaction with the environment in VR increases engagement and Presence [97]. Most of the participants in our experiment complained about not being able to interact with the animals and the trees in the safari.

Overall, out of the five hypotheses two were either fully or partially accepted. While we have noticed a strong effect of VEs to cause differences emotionally and physiologically, the direct impact of HR manipulation was subtle but noticeable in some situations such as partner valance and arousal. Participants liked the idea of being able to understand the other person's physiological state during collaboration but in the given tasks in this experiment this was not always effective. One participant (P3) said that *"... it is interesting to know the other person's HR but I do not think it changed my actions at all in the given circumstances."*

6.5.1 Limitations

We have presented the first experiment where the effects of sharing manipulated HR feedback of one collaborator to the other is measured but our experiment has a few limitations. First, our experimental environments were entertaining in nature and not relevant to real-world experiences. Our results, accordingly, may yield differences in a different set of tasks where the experiences are more serious in nature, such as remote training and tele-medicine.

Second, informed by [28], we have manipulated the HR signals within the $\pm 20\%$ range. While these manipulation levels have indicated some effects in the measured variables, a wider range of manipulation (e.g. $\pm 50\%$) might have resulted in stronger differences.

Third, besides HR there are other physiological signals that correspond to human emotions such as GSR and pupil dilation [19]. In our experiment we have not measured or shared these signals. We have noticed a trend of HR feedback manipulation resulting in a change in real HR. However we did not measure what effects it had on other physiological signals.

6.6 Conclusion

In this chapter, we have presented a study where a collaborator's HR feedback was modified and shared with another collaborator in a VE. We used two different VEs with two different levels of interaction—passive (safari) and active (shoot and survive). In each of those environments we provided two levels of manipulated HR feedback (-20% and +20%) and real HR feedback of the collaborators to each other in real time. We explored the effects of such manipulations and the different VEs in terms of real HR, emotional effects, and social presence.

We have found that nervousness and scariness in the VEs can be manipulated by providing manipulated HR feedback of one collaborator to the other. Manipulation of HR feedback affects the perceived valance and arousal levels of one another during collaboration. Our active VEs caused higher Social Presence, IOS, and PANAS than passive VEs. Overall, the utility of providing HR feedback to the other collaborator is depended on the task at hand. We suggest providing increased HR feedback where it is important to make the collaborators feel that the other collaborator is in a positive emotional state (valance). Increased HR feedback enhances the feeling of nervousness in a passive environment. We suggest that positively manipulated HR feedback can be provided in less active VEs where increasing nervousness may be useful such as in VR movies.

Chapter 7

Exploring Pupil Dilation in Emotional VR Environments

In the previous chapters, we explored the effects of sharing HR in VR environments. We also manipulated the users' HR feedback when they were in the VR environments in single-user and collaborative situations. These studies have helped us understand how users respond to HR cues - their own and another user's. These studies have also demonstrated that users prefer the auditory and haptic senses for the delivery of such cues. In this chapter, we explore pupil dilation responses in different emotional VR environments. This study was presented as a full paper in International Conference on Artificial Reality and Telexistence Eurographics Symposium on Virtual Environments (ICAT-EGVE) 2017 conference, which was held in Adelaide, Australia from 22nd October to 24th November 2017.

7.1 Introduction

In this chapter we explore pupil dilation behaviour in response to VR experiences designed to elicit emotional responses. In many VR experiences it may be beneficial to measure the user's emotional response. For example, in a VR game, the developers may want to know if the experience is exciting enough, or an artist may want to create a VR art piece that makes people feel happy. Currently, the most popular way to investigate emotions is to use subjective questionnaires, such as PANAS [129], SAM [13], and the Differential Emotions

Scale (DES) [56]. However, Emotion is also manifest through the Autonomic Nervous System (ANS) which controls changes in physiological cues such as skin conductance, facial expression, HR, body temperature, and pupil dilation, among others [5, 88, 62].

In our research we explore pupil dilation in response to different types of VR experiences, to assess if it can be used as a reliable measure of emotional response. Measuring pupil dilation has several advantages compared to other physiological measurements. Pupil dilation can be measured by using unobtrusive eye tracking hardware and there are no sensors or electrodes that need to be attached to the user. Pupil size variation is an involuntary index of ANS activity and so cannot be voluntarily controlled [88]. This means that pupil dilation can serve as a reliable physiological identifier for spontaneous responses to visual stimuli. In contrast, when using facial expressions for emotion recognition, the visually observable changes in emotional facial behaviour can be masked, inhibited, exaggerated, and faked [5]. A trained actor can easily mimic a variety of facial expressions representative of different emotional states.

Pupil dilation can also be affected by cognitive load, mental imagery effects, and by visual and auditory stimuli [72, 62, 5]. In our system, five immersive VR environments were used to evoke emotions. Each environment was designed to evoke five emotions of happiness, fear, disgust, sadness, and anxiety. The VR environment had five emotional scenarios. Every emotional VR scenario was 45 seconds in length for each emotion and participants experienced the VEs for about 5x45 seconds with five emotions. In addition to showing users the VR environments, we also added real-time HR feedback using a combination of haptic, audio, and visual channels [19]. This was implemented based on the results of the study covered in Chapter 3. Sharing of the heart-rate via different sensory channels served to heighten the emotional response elicited by the VR scenes. Overall, we found that both the negative and positive emotional segments in the VR environments increased the pupil dilation in users [19].

7.2 Related Work

Research into pupil dilation and constriction in response to light stretches back at least 100 years with the pioneering work of Reeves [95] who explored the response of one or both eyes to different amounts of brightness. He found that the pupil diameter responds differently for each individual, but the response function has the same characteristic shape. This effect has been confirmed by many researchers in the years since, such as Brown et al. [16] and Young et al. [135]. In the context of VR, this means that when a person is wearing a VR HMD their pupil diameter will change relative to the amount of light entering their eyes from the HMD.

Except for responding to light, pupil dilation also occurs in response to emotional arousal and other factors. Research into pupil dilation as an indication of negative and positive arousal has been investigated for many years. For example, Hess et al. [53] famously reported that the pupils constricted when people viewed unpleasant pictures and dilated when they viewed pleasant pictures. However, other researchers found that emotional arousal modulated the pupil dilation by increasing the pupil diameters. Bradley suggested that Hess' work had some methodological difficulties [14]. In his study he used more pictures and participants and sourced all the stimuli pictures from the International Affective Picture System (IAPS) [67]. The results showed that both negative and positive arousal pictures enlarged the pupil diameters in users compared to neutral pictures. Kawai et al. [62] also investigated pupil diameter variation by using visual stimuli with positive and negative images and they found the pupil diameter for positive emotion was smaller than for negative emotion.

Similarly, Partala et al. [88] found that when subjects were listening to different emotionally arousing audio clips, the pupil size was significantly larger during both emotionally negative and positive stimuli than during neutral stimuli. In this case they used the audio sound stimuli set called the International Affective Digitized Sounds (IADS) designed by Bradley and Lang [15] to create an emotional response to audio. Audio storytelling with

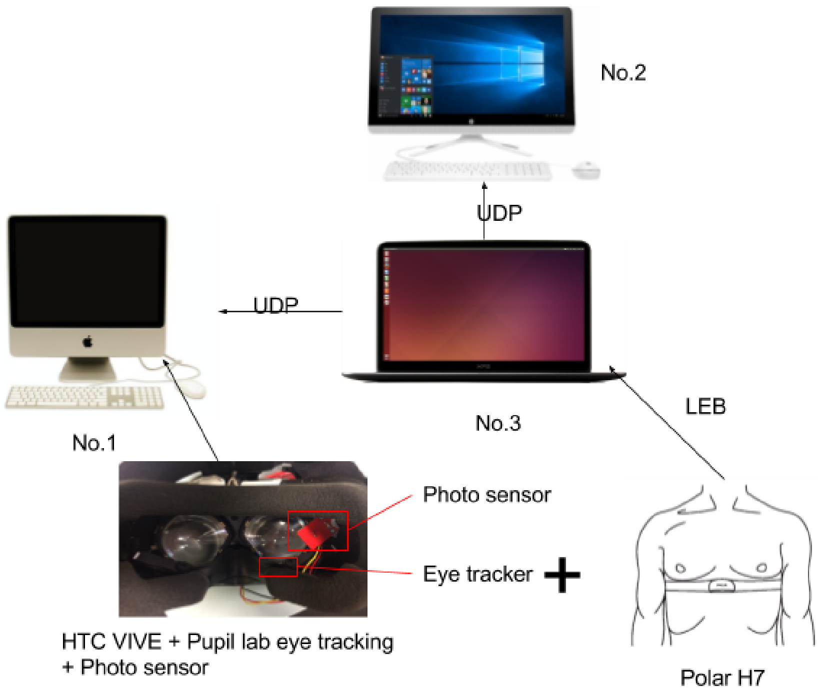


FIGURE 7.1: System Overview [19].

emotional content [5] and even pure audio tones [126] has been shown to induce pupil dilation.

From the research of Baltaci et al. [5], when the participant listened to a story designed to evoke negative arousal, the pupil dilation would be significantly larger than that in a neutral story. The pupil dilation also changed when the audio was switched from the background music to a talk.

These studies show that pupil dilation and diameter changes occur in response to emotionally arousing visual and audio content. However, although pupil dilation has been studied in many different domains, there has been little or no work studying it in VR. This is due to many factors, including the difficulty of getting access to eye-tracking hardware suitable for VR displays, proper emotional arousal scenes, and the difficulty in separating the effects of emotions, brightness, and interaction on pupil dilation.

7.3 Experimental System

To measure a user's physiological response to a VR experience, we developed the system shown in Figure 7.1. This combined input from an eye-tracker and

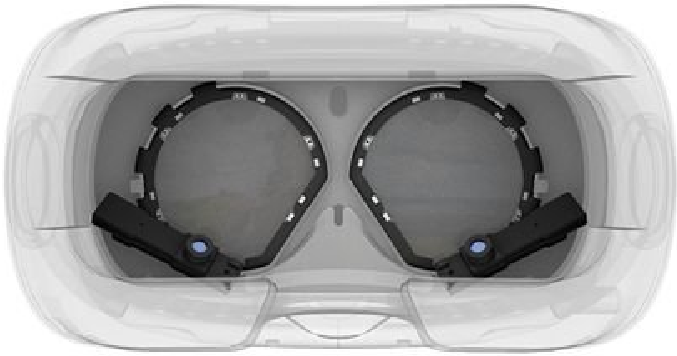


FIGURE 7.2: Pupil labs eye tracker for HTC VIVE [19]

the user's HR in response to the visual and auditory cues delivered in a VR environment.

Three computers were used to run the prototype hardware and software that was developed for this study - an iMac (No.1), a desktop computer with the Windows 10 operating system (No.2), and a laptop running Ubuntu Linux (No.3). Eye-tracking and measurement of the pupil diameter was performed on the iMac. This computer was running the Pupil Labs open source eye-tracking software [94], which captures the pupil dilation. This software works with the Pupil Labs eye-tracking hardware integrated into the HTC Vive HMD. Figure 7.2 shows the HTC Vive HMD with the integrated Pupil Labs eye tracker. The Pupil Labs HTC eye tracker tracks the eye gaze at 120 Hz with an accuracy of 0.6 degrees and can measure the pupil diameter to an accuracy of 1 mm.

In addition to this, a custom photo sensor was also mounted beside the eye-tracking camera in the HTC Vive. This photo sensor was used to measure the brightness of the HMD display elements. In this way, the VR scene brightness and the pupil dilation were both captured when the headset was worn by users. The photo sensor in our user study is a Light Dependent Resistor [90] connected to an Arduino board as shown in Figure 7.3. The range of data from Arduino was from 0 to 1023, where 0 indicates the minimum brightness while 1023 indicates the maximum. The Arduino board was connected via USB to a Windows computer (PC No.2 in Figure 7.1) running Windows 10.

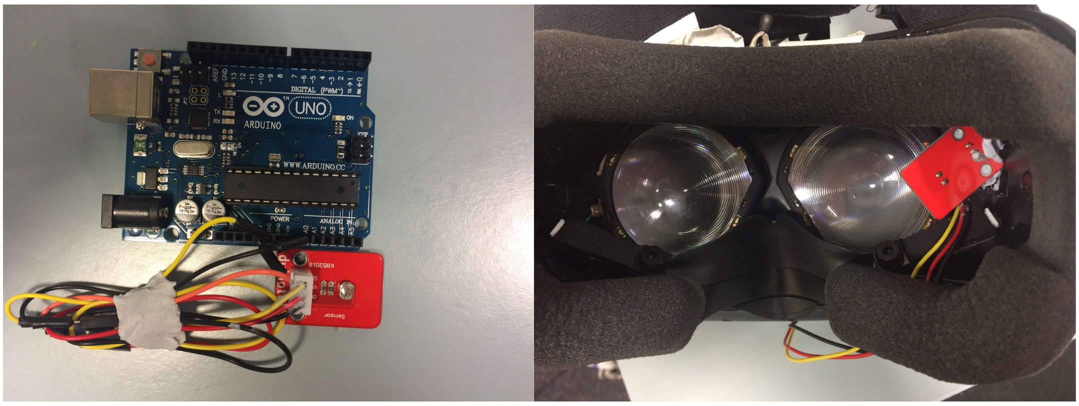


FIGURE 7.3: Left: Photo sensor and Arduino Board. Right: The photo sensor and eye tracker in HTC Vive HMD [19].

Sample VR applications were run on the No.2 computer. All of the VR scenes were built and designed in the Unity game engine. The HTC Vive HMD was connected to this computer along with the Lighthouse tracking system used to measure the user's head position. The user also held the HTC Vive handheld controllers in their hands to provide haptic cues through vibration (see below).

The final element of the system was the heart-rate recording that was measured by the No.3 computer. In this case the computer communicated with a Polar H7 HR sensor worn by the user [92], which uses Bluetooth for connection. In our user study, the sampling rate of the data streamed from the Polar H7 was 1 Hz.

The Generic Attribute Profile was used to connect the No.3 computer and the Polar H7, enabling the Polar H7 HR data to be streamed to No.3. Then the data was transferred to computer No.2, using the UDP protocol, where the HR data was visualised and presented to the user, using a variety of audio and visual cues in the VR scenes and haptic cues on HTC Vive controllers. Finally, in computer No.1, the HR data were paired and synchronized with the pupil dilation data.

The overall outcome of using this system is that we were able to show a variety of VR experiences to a user, and measure the user's HR response and their pupil diameter changes while they were in the experiences. This provides an ideal platform for us to conduct the user study described in the

FIGURE 7.4: In each of the VR environments we designed five different emotions experiences of around 4 minutes length. The experiences were:happiness (a), anxiety (b), fear (c), disgust (d), and sadness (e) [19].

next section.

7.4 Exploratory Study

With the prototype system described in the previous section, an exploratory study was conducted to measure pupil dilation response to different VR experiences. In this system, HR feedback was provided using a combination of different audio, visual, and haptic channels. The default VR scene was of a virtual African safari with grasslands, scrub and a variety of animals, as shown in Figure 7.4. At different segments in the scene users experienced different content designed to elicit an emotional response.

In our user study, we provided multi-sensory HR feedback to participants, particularly focusing on the audio, visual, and haptic senses. Visual feedback was given by displaying a red heart symbol on the screen, which changed its size proportionately to the change in HR. The auditory feedback was provided by the sound of a heartbeat played back through Logitech noise-cancelling headphones. We adjusted the volume level of the headphone to the comfort level of the participants. The haptic feedback was provided as vibrations through the handheld Vive controllers.

During the user study, users experienced five similar VR scenes and we assigned one specific set of cues to each scene. The five cues were:

- None: No visual and audio cues are provided
- Haptic-audio: The user hears the sound of their heartbeat and feels the Vive controller vibrating
- Haptic-visual: The user sees an animation of their heart beating and feels the Vive controller vibrating
- Audio-visual: The user hears the sound of their heartbeat and sees an animation of their heart beating
- All: The user experiences all of the visual, audio and haptic cues.

The presentation of cues and scenes were counterbalanced using a balanced Latin square.

The five scenes assigned with one specific cue were randomized in the user study. The VR scenes were designed to create specific emotional responses. In our user study, there were five scenes and each had five different segments designed to create a different emotional response (happiness, anxiety, fear, disgust, and sadness). For example, Figure 7.4 showed five pictures of different emotion segments in one of our five VR scenes. The happiness segment had butterflies flying around the user's virtual vehicle and beautiful flowers, green grass and trees were also in the scene. In the anxiety segment, lions were attacking another vehicle and the driver was crying for help. The fear segment had a T-Rex running and roaring towards the user's vehicle, and the disgust segment showed rotten animal bodies and blood littered along the road. Finally, the sad scenario had a wolf cub whose mother had been killed. The cub was shown walking around the mother's corpse whining.

We collected data from seven participants (one female) in the user study, with ages ranging from 27 to 58 years (M=37.1). All participants reported no hearing or vision abnormalities.

7.4.1 Procedure

After welcoming participants and explaining the study, we asked them to stand in a resting position. The user was then asked to put on the Polar H7 chest strap. The H7 was used to measure HR because it provides very accurate HR sensing when doing exercise [127]. The strap of the sensor was attached to the skin around the chest across the heart. The participants were told that the user study was a jungle safari. Their HR was visualised using audio, visual and haptic cues. During the user study they would have five conditions, haptic-audio, haptic-visual, audio-visual, all, and none of them. In the user study, they could rotate their head to see different viewpoints but they could not move their body. The visual cue of HR in the VR scene was fixed on the VR main camera so that the cue was always visible.

After this, the user put on the HTC Vive headset and a baseline VR scene was shown to perform a pupil diameter calibration. This VR scene was an empty room without anything else. The brightness in the virtual room was then changed from complete darkness to very bright whiteness over 60 seconds in nine-step increments of brightness. The change in brightness was measured by the light sensor in the HMD and the pupil diameter response to the change in brightness in the HMD was captured with the Pupil Labs hardware and software. Each user's response was different, and the relationship between the brightness and the pupil dilation for one person is shown in Figure 7.6. As expected, with increasing brightness the pupil diameter decreased. The user's pupil response to brightness variations was used as a personalized baseline to measure additional pupil diameter changes due to their emotional response.

After this, the VR scenes were played for the user and each scene was shown for around four minutes. There were five scenes in total (5x4 minutes). In the VR experience the user was standing in a vehicle that automatically moved through the virtual safari. The user could turn their heads and move their bodies slightly, but the vehicle path was pre-programmed. After each scene, there was a mandatory break of at least three minutes. While the user

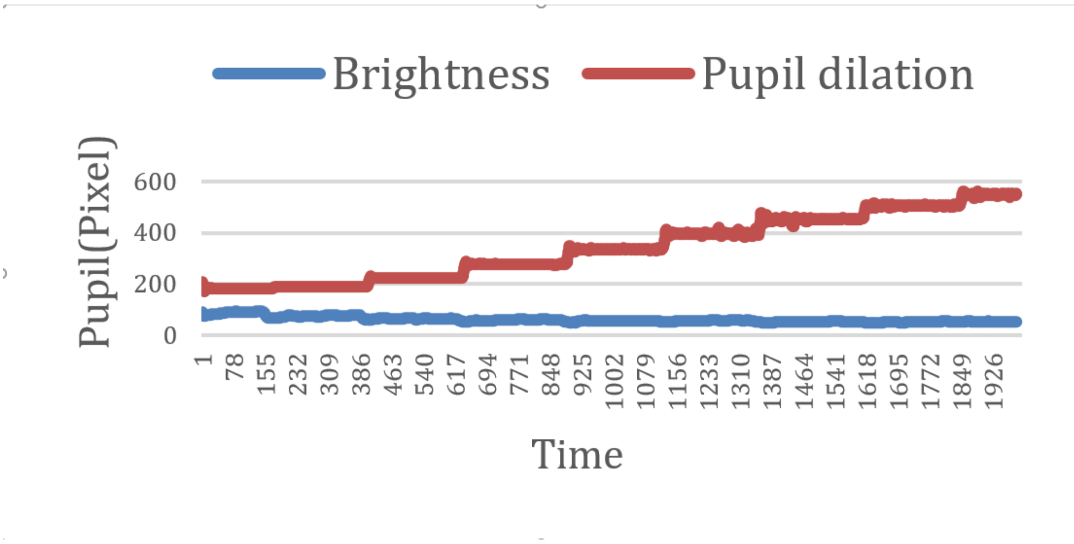


FIGURE 7.5: The trend of pupil dilation while the brightness is intensified [19].

was experiencing the VR scene, we continuously measured their HR and pupil diameter. In the next section we report on the results of this data collection.

7.5 Results

During the baseline measurement, the user experienced an empty room and the brightness changed from minimum to maximum. At this stage, we assumed that there was no emotion involved in experiencing the VR and the user's pupil size was only affected by the brightness in the headset.

The brightness steps (minimum 0, maximum 8) was divided equally into nice parts at baseline, matching the nice brightness levels. Each subject had an individual pupil response to the change in brightness. One paired data set (brightness and pupil dilation) of one subject is shown in Figure 7.5. According to the work in [128], to get the trend line of the pupil dilation response to change in brightness, a third-order polynomial was fitted to the observed data. For each subject we created a unique pupil dilation response measure according to the baseline data.

We assumed that the brightness and the pupil dilation of each participant was paired in their own curve line and the relationship of brightness and pupil dilation in the baseline is shown in Figure 7.6. The formula is shown in the figure as well. For example in Figure 7.6

$$y = -3E^{(0.6)} * x^3 + 0.0036 * x^2 - 1.5827x + 315.66$$

where x means the brightness and y means the pupil dilation at the value of the specific brightness, x.

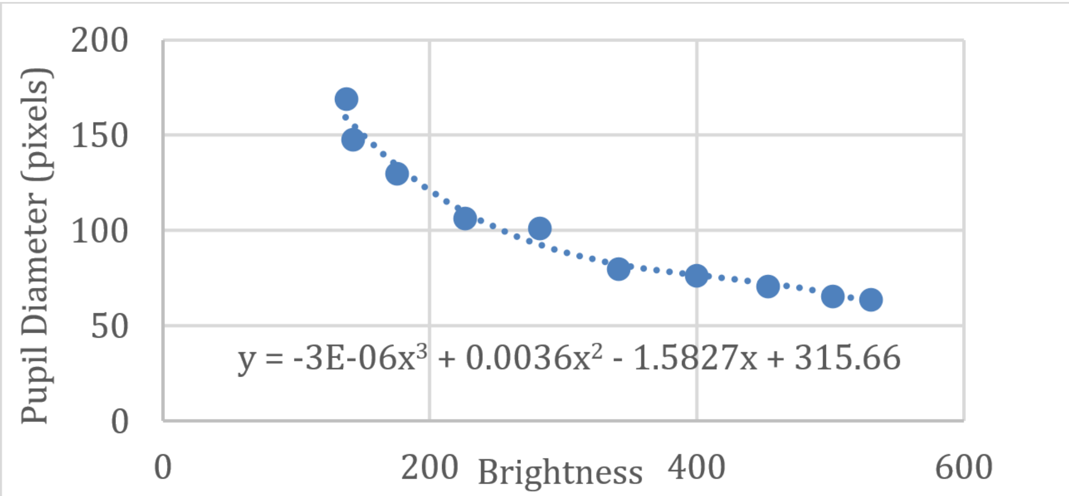


FIGURE 7.6: The relationship between brightness and pupil dilation [19].

When users experienced the emotional VR environments, the brightness and the pupil dilation were captured and recorded at 30 samples/second. The brightness at each point in time was input into the user's individual baseline formula, and the baseline pupil dilation response found. This was how much the pupil should be dilated without any extra effect due to emotional response. Assuming $pupil_{total}$ is the pupil dilation captured in the emotional VR scene, $pupil_{emotion}$ is the pupil dilation affected by the VR experience without brightness and $pupil_{brightness}$ the pupil dilation affected by the brightness, the equation

$$pupil_{emotion} = pupil_{total} - pupil_{brightness}$$

gives the pupil dilation caused by the VR experience.

Using $pupil_{emotion}$, we measured the change in pupil dilation (in % values) from the baseline and ran a two-way repeated measures ANOVA using

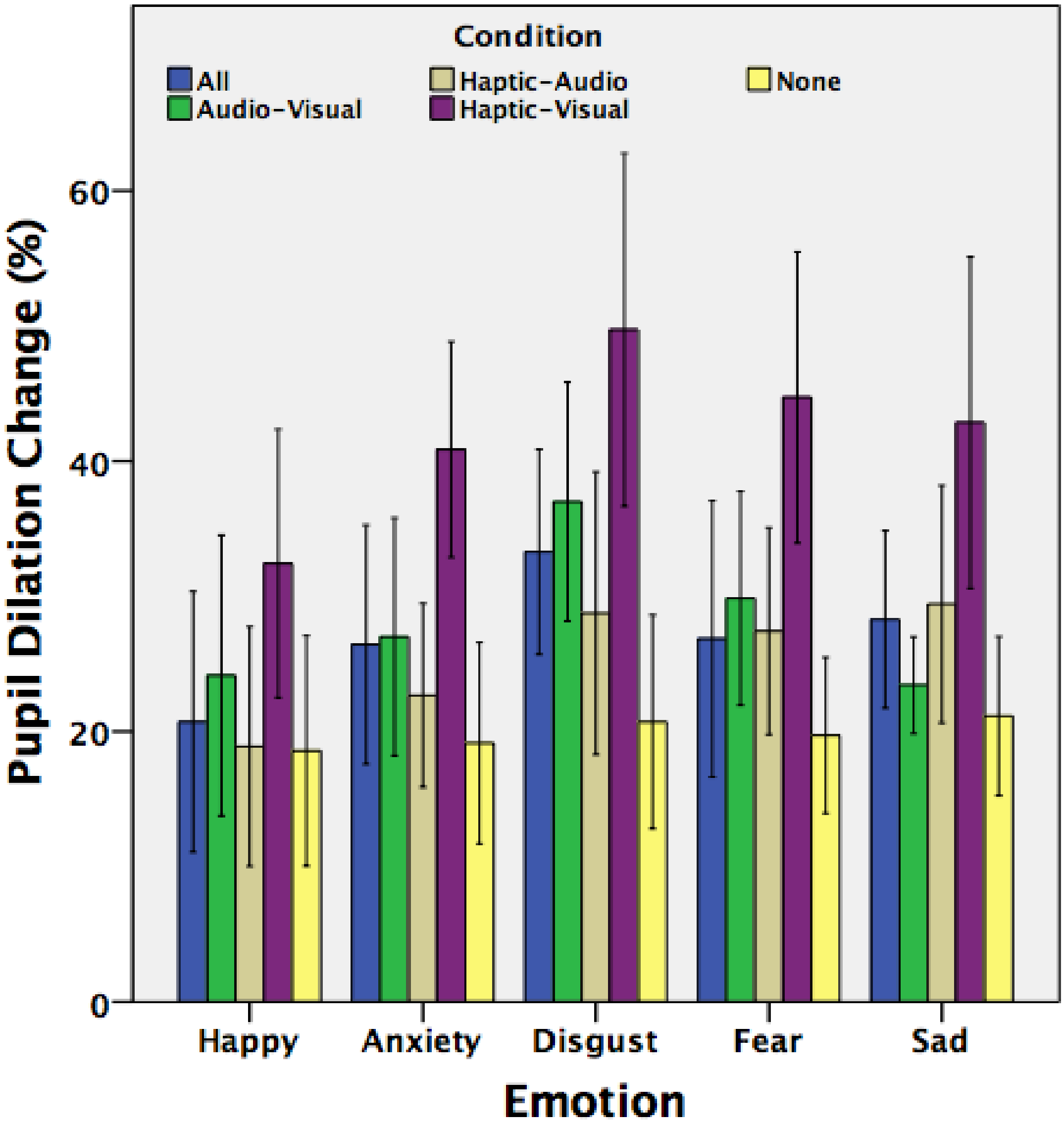


FIGURE 7.7: The Pupil Dilation Change (%) in each emotion for all conditions [19].

the data with *Emotion* and *Sensory Modality* being the two variables (Figure 7.7). We found a significant main effect of *Emotion* on pupil dilation change, F(4,24)=9.05, p<0.001, η_p^2=0.6. A pair-wise comparison with Bonferroni's adjustment found that *Disgust* had significantly higher pupil dilation change than all other emotions, and *Happy* had significantly lower pupil dilation change than all other emotions except for *Sad*.

We also found a significant main effect of *Sensory Modality* in pupil dilation change, F(4,24)=25.3, p<0.001, η_p^2=0.81. With a pair-wise comparison, we found that the *Haptic-Visual* condition had significantly higher pupil dilation

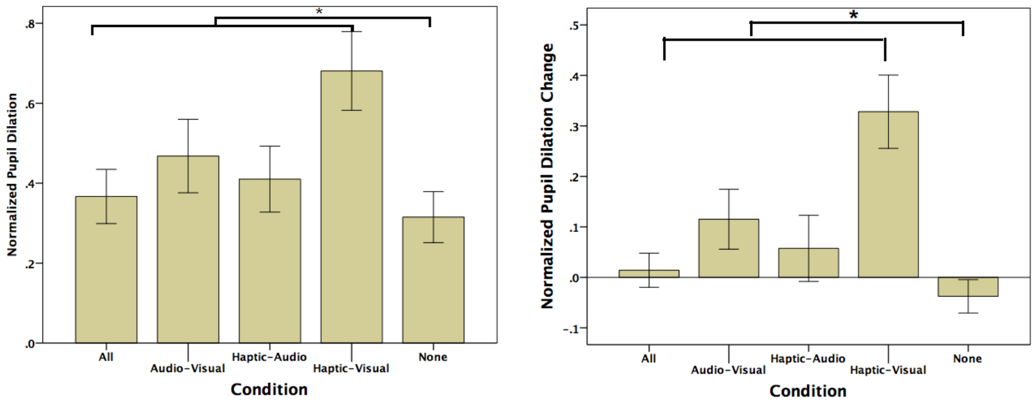


FIGURE 7.8: The normalized pupil dilation (left) and normalized pupil dilation change from baseline (right). In case of the None condition, negative dilation change indicates less dilation than in the baseline condition. Whiskers represent ± 95% confidence interval [19].

change than the *Haptic-Audio*, *Audio-Visual*, and *None* conditions.

There was a significant interaction effect of *Emotion* × *Sensory Modality*, $F(16, 96) = 2.45, p = 0.004$,$\eta_p^2$=0.29. We noticed that the pupil dilation did not change much for the *None* condition across all emotions (Figure 7.7). However, the *Haptic-Visual* and *Audio-Visual* conditions had clear changes in pupil dilation between different emotions. This shows that in the *None* condition the pupil dilation was about the same, but adding additional cues could cause a greater difference in dilation results.

In our research, three types of HR cues were shown to the participants (audio, visual and haptic). Figure 7.8 shows the average change in the percentage of pupil diameter above the baseline measure across all the VR scenes for each of the HR conditions. To compare the pupil dilation response between different conditions we used a repeated-measure ANOVA analysis on the $pupil_{total}$. We found a trend of the condition in the dilation change F(1.22,6.09)=4.33, p=0.08, η_p^2=0.46 (Figure 7.9).

However, different environments in the experiment also had different brightness, and participants looked in different directions in the immersive scenes, which also varied the brightness across participants even in the same environments. To eliminate the potential confounding effects of brightness on pupil dilation, we normalized the data for unit brightness using this formula:

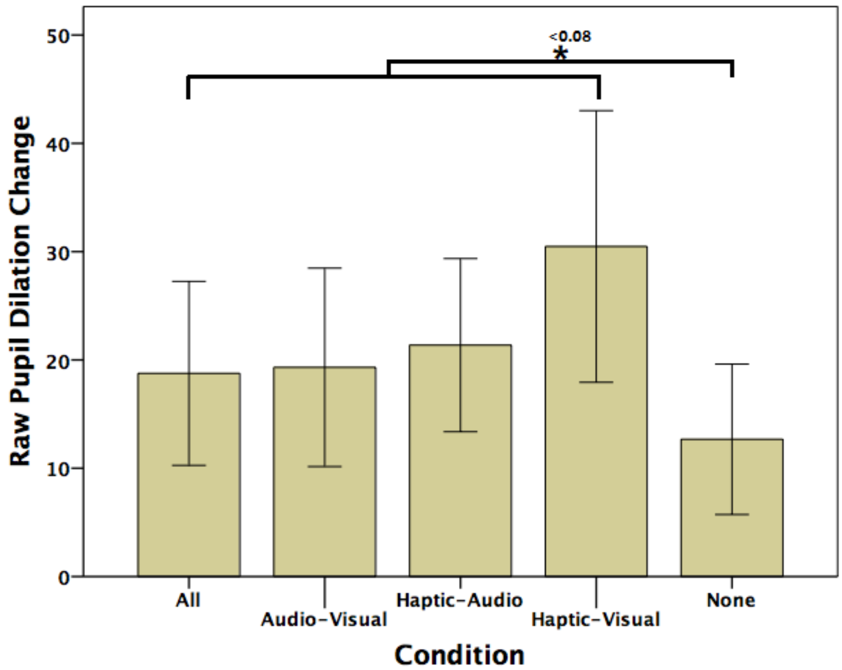


FIGURE 7.9: The raw pupil dilation changes from baseline. Whiskers represent ± 95% confidence interval [19]

normalized pupil dilation = *pupil dilation* / *brightness*.

Using a repeated-measures ANOVA, we found that the condition used to present the HR data had a significant effect on the normalized pupil dilation change (from baseline) F(2.01,10.04)=37.76, p<0.001, η_p^2=0.88 (Figure 7.8). The data violated the assumption of sphericity so we applied a Greenhouse-Geisser adjustment. A pairwise comparison with Bonferroni's adjustment revealed that the *Haptic-Visual* condition caused significantly higher pupil dilation change than all other conditions with $p < 0.01$.

7.6 Discussion

The primary purpose of this study was to explore if pupil dilation could be used to monitor the user's emotional arousal states in the VR experience. From previous research, using images and audio cues, we know that pupil dilation could increase in response to emotional arousal. We also know that VR scenes can evoke emotions in users.

For our research, we designed five VR scenes and each scene had five different emotion segments, including happiness, sadness, fear, disgust, and anxiety. These five emotion segments were designed to evoke specific emotions when the user experienced the VR scenes. From Figure 7.7, all the emotional scenarios in the five scenes increased the pupil dilation in the users. From the knowledge of investigating pupil responses to emotional arousal images or audio, both negative and positive arousal images or audio can result in enlarged pupils [88, 5, 14]. The results are consistent with those in arousal images and audio cues and also demonstrated that the scenes that we designed could evoke negative or positive arousal in users.

In our user study, the condition of haptic-visual cues in the VR scenes produced the largest increase in pupil dilation of the five conditions, as shown in Figure 7.7. The visual cue in the VR scene was scaled according to the real-time HR. The cue was a heart shape, shown in the "a" picture in Figure 7.4. When the virtual heart was beating, it was like a red cue flashing in front of the users. When the HR increased, the cue would be scaled to be faster and larger. When experiencing the VR scene, the user had to pay some attention to the virtual heart shape. In Kahneman et al.'s [60] research, a high-level cognitive workload could enlarge pupil dilation. In our study, it is likely that the visual cue increased the cognitive workload, leading to an increase in the pupil diameter. This is visible in all conditions that made use of the visual cue. The use of the visual cue appeared to force the users to divide their attention between objects in the VR scene and visual representation of the heart-beat seen in the HUD interface.

Another plausible explanation for the haptic-visual condition demonstrating the greatest pupil dilation increase could be that visualising physiological cues in the VR scenes is distracting to users. In addition, we also hypothesize that the presence of a visual physiological cue induces an added layer of emotional complexity that is reflected in the large pupil dilation percentage seen in this condition. Post-study interviews consisting of open-ended questions regarding cue preferences and UI design demonstrated that a majority of the participants preferred auditory feedback. Participants also indicated that they found the visual cue distracting and that it had a negative impact on their experience in the virtual environment. There is potentially a confounding effect of visual cue distracting and annoying participants and consequently evoking additional emotion on top of the targeted emotions in the VR experience, which may have led to an additional change in pupil dilation. However, this effect needs to be investigated further.

At the same time, we noticed that the None condition did not have any noticeable pupil dilation change for different emotions. This indicates that not having HR feedback causes lower emotional arousal than when having it. This leads to an interesting finding, which needs further validation, that in the presence of HR feedback, change in pupil dilation can be used as an indicator of emotion.

7.7 Conclusions

In this chapter, we investigated pupil variation caused by using positive or negative affective VR scenes. From the results, the pupil diameters in both positive and negative emotional segments increased. We noticed that haptic-visual feedback increased the pupil diameter the most for all emotions, while not having any feedback cues produced the least pupil dilation. It is clear from our results that pupil dilation is effected by VR environments and more studies are needed to establish the relationship between pupil dilation and emotional arousal in VR.

Currently some interesting research is being carried out by the machine-learning community to measure emotion from physiological signals such as HR and GSR. Compared to physiological signals, pupil dilation varies much faster [88] and could also reflect emotional arousal. In the future, pupil dilation could also be used to measure emotion similar to these other physiological signals.

In recent research, subjective surveys are the most popular methods for measuring emotional arousal. Physiological signals such as HR and GSR are attracting significant attention for measuring emotions. However, these objective measurements are limited. With more research, pupil dilation could be adopted as an objective measurement of emotion, particularly in the human-computer interaction domain.

From our results it can be confirmed that pupil dilation reflects arousal in VR. But we do not know the extent to which pupils are dilated in response to specific arousal. The relationship between the brightness and pupil dilation has been explored by many researchers, such as Watson et al. [128], Winn et al. [132] and Barten et al. [9]. Whether the relationship between arousal and pupil size can be formulated in a similar way as the relationship between brightness and pupil dilation is an interesting topic for future research.

There are a number of areas of improvement for future research. During our study, every participant had to take off the Vive headset after finishing each scene. After that, they put the headset on again. As the headset moved and its position changed on the head, the pupil distance to the camera might have been changed as well, which we did not to take into account in our study. In the future, we will just use one reasonably longer scene to measure the pupil dilation.

In this experiment, we designed the VR environments ourselves. The graphics quality was not as good as the commercially available VR games. In the future, we will validate our findings using commercial games. This work is one of the initial explorations of pupil dilation in VR environments. We expect to build more research on top of this and hope our results will inspire other VR researchers to consider investigating pupil dilation as a measure of emotional response in VR.

Chapter 8

Conclusions and Future Work

This thesis has investigated the possibility of sharing emotions in VR using physiological signals. To conduct this research, we designed two types of users studies. One is users' HR was shared to himself/herself via Audio-Haptic feedback and the other is the users' HR was shared between the users when they were in the same VEs.

We have gone through a brief history of VR and the important stages of VR development in Chapter 2. Also, we reviewed the previous research on emotions in VR. The research included the work investigating the triggers of the emotions, like weather [33, 100, 8], light [35, 6], experiences [29, 107] etc. we also reviewed the VR therapy research which found the emotions including anxiety and fear could be evoked during the treatment to patients, like treatments of the spider phobia, flying phobia, social phobia, Posttraumatic Stress Disorder (PTSD) etc. In the last session of Chapter 2, we reviewed the research on sharing physiological signals in different platforms, such as desktop, mobile and VR and we found sharing physiological signal cues between users could help them understand each other's emotional states and also increase connectivity and in turn enhance the sense of empathy for one another.

In Chapter 3, we presented four different multi-sensory visualisations of HR data in immersive VR experiences. The goal was to explore the multi-sensory design space for providing physiological feedback cues in the VEs and validate which feedback cue is preferred by the user. This is fundamental for our future work in sharing emotional cue in users. Since we need to assure users could notice the emotional states effectively in the VEs especially when we were reviewing previous research and did not found any work which systematically investigated the physiological feedback in VEs.

In Chapter 4, we have presented a study in VR where the effect of manipulating multi-sensory HR feedback on user emotions was investigated. In the study, we designed five manipulations (-30%,-15%, 0, +15%, and +30%) of HR feedback in the VEs and found that interest, excitement, scariness, nervousness, and fear can be enhanced by providing manipulated HR feedback in the VEs. This is an interesting finding for VR researchers and virtual experience designers, as they can modulate a user's emotion in a more controlled way than previously, by simply providing and manipulating HR feedback.

In Chapter 5, we investigated the effects of sharing real-time multi-sensory HR feedback between users in different collaborative VEs. Three VEs were designed including furniture arrangement, escape room and exploration. In the study, two conditions were involved, one with HR feedback (ON group) while the other without HR feedback (OFF group). We found compared to the feedback OFF group, the feedback ON group had more dominance when exposed to VR, generated more positive affect for unit negative affect, noticed the presence of the collaborator more, and felt the collaborator's emotional state more. The results show the benefits of providing HR feedback in collaborative VR environments.

In Chapter 6, we have presented a study where a collaborator's HR feedback was modified and shared with another collaborator in a VE. We used two different VEs with two different levels of interaction—passive (safari) and active (shoot and survive). In each of those environments we provided three levels of manipulated HR feedback (-20%, 0%, and +20%) of the collaborators to each other in real time. We explored the effects of such manipulations and the different VEs in terms of real HR, emotional effects, and social presence.

In Chapter 7, we investigated pupil variation caused by using positive or negative affective VR scenes. To our knowledge, the prototype we designed in this study was the first one integrating both of pupil dilation sensors and photo sensors into an HMD and was used to measure the pupil dilation caused by the emotion after the compensation of brightness. From the results, the pupil diameters in both positive and negative emotional segments increased. We noticed that haptic-visual feedback increased the pupil diameter the most for all emotions, while not having any feedback cues produced the least pupil dilation.

8.1 Limitations

In this thesis, we conducted five studies and had some limitation in the research in the system designs, participants recruitment, questionnaires selected, and physiological data collection.

- Participants: Since all the studies were conducted at the University of South Australia, we recruited the participants on campus and some of subjects participated in more than one study. The campus where the studies run does not have too many female students and most of our subjects were male.
- Limited HR feedback designs: In Chapter 3, we designed the heartbeat audio feedback, haptic feedback on controllers and visual heart shape in VEs. From the results of questionnaires, we found Audio-Haptic feedback was the preference of users and could convey the emotion states properly in users. However, when we conducted the study in Chapter 6 where the user had more workload, we found subjects could not notice the feedback appropriately. The reason is maybe the strength of vibration on controllers is not powerful enough because of the limitation of actuators in HTC Vive controllers. We could use more powerful haptic actuators in our future studies, as the prototype in [80].
- Limited Questionnaires: In Chapter 3, we designed a five-point Likert-scale rank questionnaire which had some English mistake. In Chapter 5 and Chapter 6, we only used the social presence questionnaire by Harms and Biocca [47] and others could be added in the studies in the future, like social presence questionnaire by Bailenson [4].

- Emotion VR scenes: In Chapter 3 and 4, we designed five emotional VEs from what we learned in the International Affective Picture System (IAPS) [66] and the International Affective Digital Sounds (IADS) [12] databases, and the literature on emotion induction in VR. For the VEs, we conducted a pilot study with four subjects and did not conduct a systematic study to validate the emotional VEs. However, from the results of PANAS results in Chapter 4, we found the emotions affected by the manipulation of HR feedback were similar or the same emotions we proposed to evoke in our emotional EVs.

- Limited physiological resources: In the thesis, we only shared the HR feedback in users and captured and analysed the HR data and we did not get any significant results from the HR data analysis. Maybe the heart rate variability could show more messages in the emotion results.

8.2 Conclusions

Five user studies were designed and processed during my PhD research. We have learned some lessons from these user studies.

- From results in the user study in Chapter 3, we found a VR system can increase the overall user experience by following these design guidelines: (1) the system should provide feedback of physiological data such as HR; (2) if possible, the feedback should be provided primarily through audio and haptic channels.

- In the study of Chapter 4, we noticed that manipulating HR can increase interest, excitement, scariness, nervousness, and fear. The effects were most noticeable when either +15% or -15% HR feedback was provided. We would recommend providing slightly increased or decreased HR feedback when the application requires an increase in emotions.

- In Chapter 5 and Chapter 6, the studies showed that via sharing the physiological cues, the subjects could have more presence of the collaborator and felt the collaborator's emotional state more.
- In Chapter 7, we designed an HMD integrated with photo sensors and pupil dilation sensors to measure the emotion. From the results in the study, we found the pupil diameters in both positive and negative emotional segments increased. However, more work is needed to validate the relationship between pupil dilation and emotion in VR.

8.3 Future Work

In my PhD research, we investigated sharing emotions in VEs via physiological signal and learned some lessons from the studies. There are some directions for future work to continue the research undertaken in this thesis.

In this thesis, we did not investigate sharing the emotion cues directly instead of physiological cues in the virtual world. In the future, we could use machine learning technology to analyse the physiological signals, such as EEG, HR and GSR in real time and get the emotions of participants. It could be very promising to share emotions cues which could help users understand his/her partner's emotions straightly, like the research in [73] called "empathy glasses", showing the emoji and helping enhance the collaboration. Also, it will be interesting to investigate how to display the real emotion cues in the virtual world, like the investigation in [10, 74].

In the future, we will also explore more serious collaborative environments such as training and surgery where HR feedback may provide more utility than the entertaining VEs used in this experiment, especially for conveying information about stress levels. The method of providing feedback is another area to explore further.

As we noticed in the active environments in Chapter 5 and Chapter 6, participants did not notice the feedback as much. Maybe the subjects were focusing on the action with the tasks in VEs. So, it will be interesting to explore how the feedback can be made more salient in these kinds of environments without compromising the experience, for example, providing emotional cues adaptively based on their attention, cognitive, and emotional states.

In Chapter 5 and Chapter 6, we found sharing the physiological cue in user in the VEs could help user experience higher levels of social presence. In the future, we could investigate sharing the emotional cue in VEs in VR therapy research with accompanying the patients during the treatment. Whether the high social presence in VEs could help the treatment is interesting and meaningful. We found emotions could be affected by the manipulated HR feedback. In the future, we could investigate the VR exposure treatment by conveying the manipulated physiological feedback to patients.

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Appendix A

Questionnaires

This section presents the questionnaires used in the user studies in Chapter 5 and Chapter 6. The PANAS and SAM questionnaires were used in Chapter 3 and Chapter 4.

All the data and documents of user studies during my PhD research are here: https://drive.google.com/drive/u/0/folders/1I6RNut6PtWTni1SI6aZA TSElnpcK21Ir

Subjective Questionnaire

*Required

1. **Participant Number** *

2. **Condition** *

   Mark only one oval.

   - PE
   - NU
   - NE

3. **Environment** *

   Mark only one oval.

   - Active
   - Passive

PANAS

This scale consists of a number of words that describe different feelings and emotions. Read each item and then list the number from the scale below next to each word. Indicate to what extent you and your partner (in your opinion) felt this way while experiencing the VR environment.

1 = Very Slightly or Not at All
2 = A Little
3 = Moderately
4 = Quite a Bit
5 = Extremely

4. **You nterested** *

   Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

5. **Partner nterested** *

   Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

6. **You - Distressed** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	⬭	⬭	⬭	⬭	⬭	Extremely

7. **Partner - Distressed** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	⬭	⬭	⬭	⬭	⬭	Extremely

8. **You - Excited** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	⬭	⬭	⬭	⬭	⬭	Extremely

9. **Partner - Excited** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	⬭	⬭	⬭	⬭	⬭	Extremely

10. **You - Upset** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	⬭	⬭	⬭	⬭	⬭	Extremely

11. **Partner - Upset** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	⬭	⬭	⬭	⬭	⬭	Extremely

12. **You - Strong** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	⬭	⬭	⬭	⬭	⬭	Extremely

13. **Partner - Strong** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

14. **You - Guilty** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

15. **Partner - Guilty** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

16. **You - Scared** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

17. **Partner - Scared** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

18. **You - Hostile** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

19. **Partner - Hostile** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

20. **You - Enthusiastic** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

21. **Partner - Enthusiastic** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

22. **You - Proud** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

23. **Partner - Proud** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

24. **You rritable** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

25. **Partner rritable** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

26. **You - Alert** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All						Extremely

27. **Partner - Alert** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

28. **You - Ashamed** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

29. **Partner - Ashamed** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

30. **You nspired** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

31. **Partner - Inspired** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

32. **You - Nervous** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

33. **Partner - Nervous** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

34. **You - Determined** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

35. **Partner - Determined** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

36. **You - Attentive** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

37. **Partner - Attentive** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

38. **You - Jittery** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

39. **Partner - Jittery** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

40. **You - Active** *
Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

41. **Partner - Active** *

Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

42. **You - Afraid** *

Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

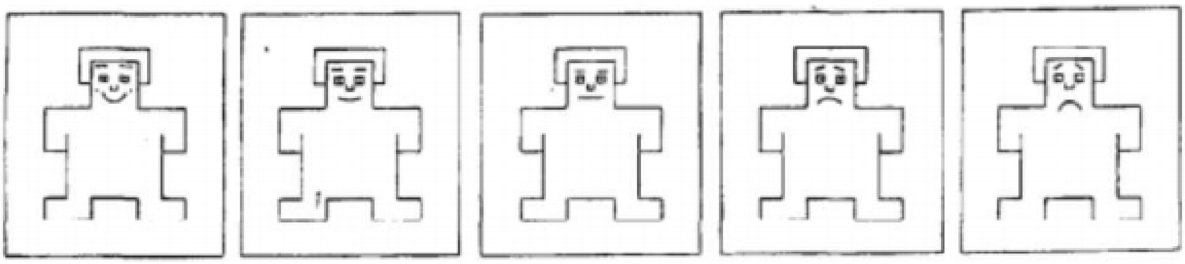
43. **Partner - Afraid** *

Mark only one oval.

	1	2	3	4	5	
Very Slightly or Not at All	◯	◯	◯	◯	◯	Extremely

SAM Questionnaire

Positive or negative emotional state



44. **How were YOU feeling emotionally when in the game?** *

Please enter a number between 1 and 5 based on the above image. 1= Left most, 5 = Right most.

Mark only one oval.

1	2	3	4	5
-	-	-	-	-

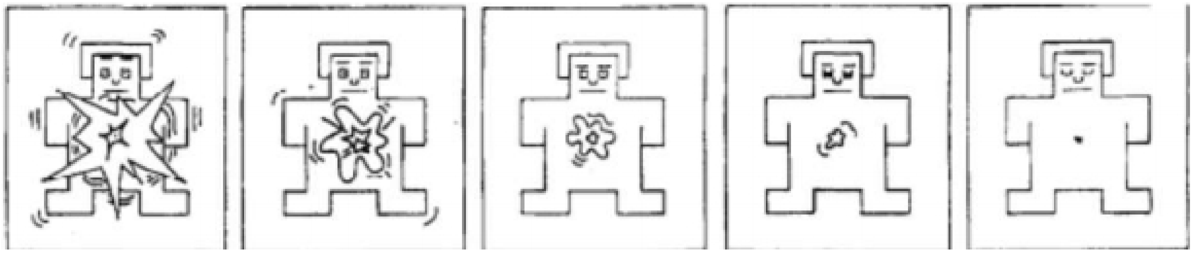
45. **How were your PARTNER feeling emotionally when in the game?** *

Please enter a number between 1 and 5 based on the above image. 1= Left most, 5 = Right most.

Mark only one oval.

1	2	3	4	5
-	-	-	-	-

Arousal



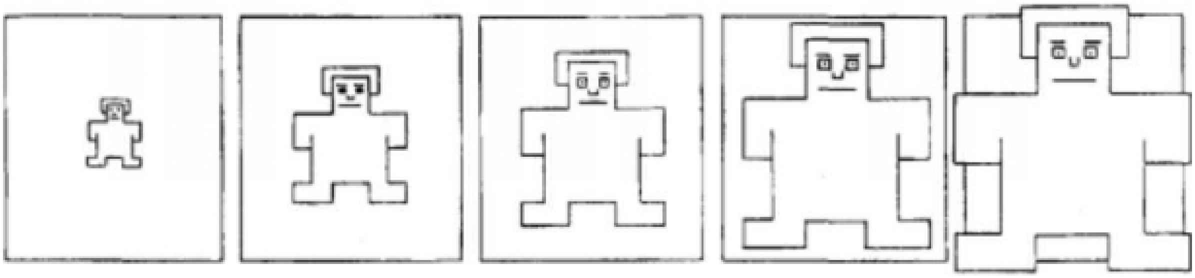
46. **How aroused were YOU feeling when in the game?** *
Please enter a number between 1 and 5 based on the above image. 1= Left most, 5 = Right most. *** Arousal is the state of being physiologically alert, awake, and attentive.
Mark only one oval.

1	2	3	4	5

47. **How aroused were your PARTNER feeling when in the game?** *
Please enter a number between 1 and 5 based on the above image. 1= Left most, 5 = Right most. *** Arousal is the state of being physiologically alert, awake, and attentive.
Mark only one oval.

1	2	3	4	5

Dominance



48. **How dominant were YOU feeling when in the game?** *
Please enter a number between 1 and 5 based on the above image. 1= Left most, 5 = Right most.
Mark only one oval.

1	2	3	4	5

49. **How dominant were your PARTNER feeling when in the game?** *
Please enter a number between 1 and 5 based on the above image. 1= Left most, 5 = Right most.
Mark only one oval.

1	2	3	4	5

Subjective Questions

50. **How much attention did you pay to your partner's heart rate when in the game?** *
Mark only one oval.

	1	2	3	4	5	
Very inattentive	◯	◯	◯	◯	◯	Very attentive

51. **How much do you think that the heart rate visualization deteriorated or enhanced your experience when in the game?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly deteriorated	◯	◯	◯	◯	◯	◯	◯	Strongly enhanced

Collab VR- Usability

*Required

1. **Participant Number** *

2. **Environment** *

Mark only one oval.

- Active
- Passive

3. **Condition** *

Mark only one oval.

- PE
- NU
- NE

4. **How strongly did you feel the other person's heart rate during the task?** *

Mark only one oval.

	1	2	3	4	5	
Not At All						Very Strongly

5. **How much did you feel the other person's emotional state during the task?** *

Mark only one oval.

	1	2	3	4	5	
Not At All						Very Much

6. **How confused did you get with the heart rate feedback?** *

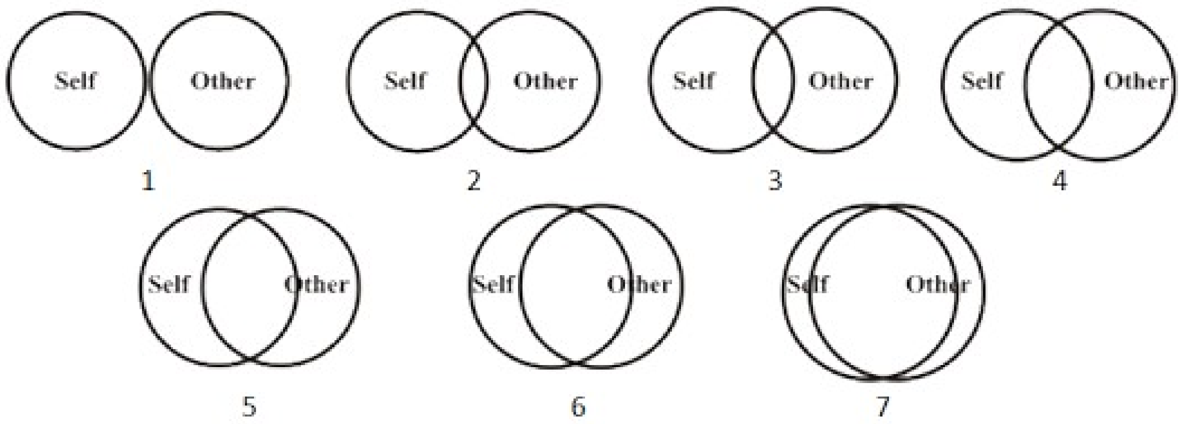
Mark only one oval.

	1	2	3	4	5	
Not At All						Very Confused

7. **How much do you think your collaborator helped you in the task?** *
Mark only one oval.

	1	2	3	4	5	
Not At All	⬭	⬭	⬭	⬭	⬭	Very Much

IOS Scale



8. **Please select a number for the respective images that best describes your relationship with the collaborator during this task.** *
Mark only one oval.

1	2	3	4	5	6	7
⬭	⬭	⬭	⬭	⬭	⬭	⬭

Collab VR - Social Presence (Co-presence)

Please respond to the questions on a scale of 1 to 7.

9. **I noticed my collaborator** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly agree

10. **My collaborator noticed me** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly agree

11. **My collaborator's presence was obvious to me** *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

12. **My presence was obvious to my collaborator** *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

13. **My collaborator caught my attention** *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

14. **I caught my collaborator's attention** *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

Collab VR - Social Presence (Attention)

Please respond to the questions on a scale of 1 to 7.

15. **I was easily distracted from my collaborator when other things were going on.** *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

16. **My collaborator was easily distracted from me when other things were going on.** *

Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

17. **I remained focused on my collaborator throughout our interaction.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

18. **My collaborator remained focused on me throughout our interaction.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

19. **My collaborator did not receive my full attention** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

20. **I did not receive my collaborator's full attention** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

Collab VR - Social Presence (Understanding)

Please respond to the questions on a scale of 1 to 7.

21. **My thoughts were clear to my collaborator.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

22. **My collaborator's thoughts were clear to me.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee								Strongly agree

23. **It was easy to understand my collaborator.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	◯	◯	◯	◯	◯	◯	◯	Strongly agree

24. **My collaborator found it easy to understand me.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	◯	◯	◯	◯	◯	◯	◯	Strongly agree

Collab VR - Social Presence (Bahavioral Independence)

Please respond to the questions on a scale of 1 to 7.

25. **My behavior was often in direct response to my collaborator's behavior.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	◯	◯	◯	◯	◯	◯	◯	Strongly agree

26. **The behavior of my collaborator was often in direct response to my behavior.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	◯	◯	◯	◯	◯	◯	◯	Strongly agree

27. **I reciprocated my collaborator’s actions.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	◯	◯	◯	◯	◯	◯	◯	Strongly agree

28. **My collaborator reciprocated my actions.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly disagee	◯	◯	◯	◯	◯	◯	◯	Strongly agree

Collab VR - Comments

29. **Please write any comment that you may have about the feedback, environment, and the experiment in general.**